Exhibit L

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US 6,176,837

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INVENTORS:	Foxlin, Eric M.
TITLE:	Motion tracking system
APPLICATION NO:	US199862442A
FILED:	17 APR 1998
ISSUED:	23 JAN 2001
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jc523 U.S. PTO
09/062442
04/17/98

Class	Subclass
600	595

ISSUE CLASSIFICATION

PATENT NUMBER
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6176837

U.S. UTILITY PATENT APPLICATION

O.I.P.E.	PATENT DATE
MC SCANNED MN Q.A. DMW	JAN 23 2001

SECTOR	CLASS	SUBCLASS	ART UNIT	EXAMINER
	600	595	3736	Mimer

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CERTIFICATE
JUN 18 2002
OF CORRECTION

PREPARED AND APPROVED FOR ISSUE

ISSUING CLASSIFICATION

ORIGINAL		CROSS REFERENCE(S)						
CLASS	SUBCLASS	CLASS	SUBCLASS (ONE SUBCLASS PER BLOCK)					
600	595	600	587					
INTERNATIONAL CLASSIFICATION		128	897					
A61B 5/103								
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☐ Continued on Issue Slip Inside File Jacket

Formal Drawings(___shts) set____

☐ TERMINAL DISCLAIMER	DRAWINGS			CLAIMS ALLOWED	
	Sheets Drwg.	Figs. Drwg.	Print Fig.	Total Claims	Print Claim for O.G.
	16	19	1	47	1

☐ a) The term of this patent subsequent to ________ (date) has been disclaimed.	Charles Marmor, II (Assistant Examiner) 3/6/00 (Date)	NOTICE OF ALLOWANCE MAILED 03/09/00
☐ b) The term of this patent shall not extend beyond the expiration date of U.S Patent. No. ________	CARY O'CONNOR SUPERVISORY PATENT EXAMINER GROUP 3700 Cary O'Connor (Primary Examiner) 3/9/00 (Date)	ISSUE FEE Amount Due: $1210.00 Date Paid: 6/18/00
☐ c) The terminal ____months of this patent have been disclaimed.	K. Turner (Legal Instruments Examiner) ____ (Date)	ISSUE BATCH NUMBER J33

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Form PTO-436A
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ISSUE FEE IN FILE

(LABEL AREA)

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6,176,837

MOTION TRACKING SYSTEM

Transaction History

Date	Transaction Description
4/21/1998	Initial Exam Team nn
5/7/1998	IFW Scan & PACR Auto Security Review
5/7/1998	IFW Scan & PACR Auto Security Review
5/11/1998	IFW Scan & PACR Auto Security Review
5/20/1998	Notice Mailed--Application Incomplete--Filing Date Assigned
10/2/1998	Application Dispatched from OIPE
10/2/1998	Application Is Now Complete
12/11/1998	Case Docketed to Examiner in GAU
4/19/1999	Information Disclosure Statement (IDS) Filed
4/19/1999	Information Disclosure Statement (IDS) Filed
6/11/1999	Non-Final Rejection
6/15/1999	Mail Non-Final Rejection
12/20/1999	Response after Non-Final Action
12/20/1999	Request for Extension of Time - Granted
12/30/1999	Date Forwarded to Examiner
3/9/2000	Mail Notice of Allowance
3/9/2000	Notice of Allowance Data Verification Completed
6/13/2000	Issue Fee Payment Verified
6/13/2000	Workflow - Drawings Finished
6/13/2000	Workflow - Drawings Matched with File at Contractor
6/13/2000	Workflow - Drawings Received at Contractor
6/13/2000	Workflow - Drawings Sent to Contractor
10/3/2000	Workflow - Complete WF Records for Drawings
10/5/2000	Application Is Considered Ready for Issue
1/5/2001	Issue Notification Mailed
1/23/2001	Recordation of Patent Grant Mailed
5/30/2002	Post Issue Communication - Certificate of Correction

jc523 U.S. PTO
09/062442
04/17/98

PATENT APPLICATION

09062442

INITIALS APR 2 8 47

CONTENTS

No.	Item	Date received (Incl. C. of M.) or Date Mailed	No.	Item	Date received (Incl. C. of M.) or Date Mailed
1.	Application Pty papers.	D	42.		
2.	1 1/2 declaration	5/18/98	43.		
3.	Sup. Dec.	9-21-98	44.		
4.	Ext. of Time	9-21-98	45.		
5.	Print Out	4-19-99	46.		
6.	6-11 Reg 3 mo	6-15-99	47.		
7.	Ext. of Time 3mo Amdt A	12-20-99	48.		
8.	ALLOWANCE	3/9/00	49.		
9.	Formal Drawings(16 shts)set 1	6-13-00	50.		
10.	Request for C of C	1-8-02	51.		
11.	Director's Report	4-25-02	52.		
12.			53.		
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ISSUE SLIP STAPLE AREA (for additional cross references)

POSITION	INITIALS	ID NO.	DATE
FEE DETERMINATION	B.K	00245	4-23-98
O.I.P.E. CLASSIFIER		13	4/29/98
FORMALITY REVIEW	[illegible]	71448	5-15-98

INDEX OF CLAIMS

✔	Rejected	N	Non-elected
=	Allowed	I	Interference
— (Through numeral)	Canceled	A	Appeal
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Final	Original	6/7/99	3/6/00	Date
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If more than 150 claims or 10 actions
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SEARCHED

Class	Sub.	Date	Exmr.
600	587 595	6/2/99	Com
364	478.01	6/2/99	Com
348	169	6/2/99	Com
367	117 118	6/2/99	CAM
128	898 897	6/2/99	Com
73	488 503.3 504.03 510 514.01	6/2/99	Com
Updated		3/6/00	Com

SEARCH NOTES
(INCLUDING SEARCH STRATEGY)

	Date	Exmr.
APS Search Search history fastened to inside center flap	6/3/99	Com
Updated Using EAST	3/6/00	Com

INTERFERENCE SEARCHED

Class	Sub.	Date	Exmr.
As Above		3/6/00	Com

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APS Search

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     (FILE 'USPAT' ENTERED AT 14:21:58 ON 03 JUN 1999)
L1          102 S MOTION TRACKING
L2         1211 S MOTION (6A) TRACKING
L3          143 S L2 AND INERTIA
L4            7 S L2 AND INERTIAL MEASUREMENT
L5           81 S L2 AND ACOUSTIC#
L6            1 S L2 AND (ACOUSTIC (6A) MEASUREMENT)
L7            0 S L2 AND (ACOUSTIC (6A) RANGING)
L8           88 S L2 AND (ULTRASOUND OR ULTRASONIC)
L9           14 S L2 AND (TRANSMITTER AND MICROPHONE)
L10           7 S L2 AND (ORIENTATION (6A) ESTIMATE)
L11          11 S L2 AND (LOCATION (6A) ESTIMATE)
L12           5 S L2 AND (DRIFT (W) (COMPENSATION OR COMPENSATOR))
L13          77 S L2 AND KALMAN
L14         150 S L3 OR L4
L15         145 S L5 OR L6 OR L8
L16           9 S L14 AND L15
L17           0 S L14 AND LL9
L18           1 S L14 AND L9
L19           1 S L16 AND L18
L20           8 S L15 AND L9
L21           0 S L16 AND L10
L22           0 S L16 AND L11
L23           0 S L16 AND L12
L24           0 S L16 AND L13
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SERIAL NUMBER	FILING DATE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
09/062,442	04/17/98	600	3737	09970002001

APPLICANT

ERIC M FOXLIN, ARLINGTON, MA.

CONTINUING DOMESTIC DATA*******************
VERIFIED

None
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371 (NAT'L STAGE) DATA*******************
VERIFIED

None
EM

FOREIGN APPLICATIONS**********
VERIFIED

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FOREIGN FILING LICENSE GRANTED 05/18/98

Foreign Priority claimed ☐yes ☒no 35 USC 119 (a-d) conditions met ☐yes ☒no ☐Met after Allowance Verified and Acknowledged EM Examiner's Initials ______ Initials	STATE OR COUNTRY	SHEETS DRAWING	TOTAL CLAIMS	INDEPENDENT CLAIMS
	MA	16	15	6

ADDRESS

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TITLE

MOTION TRACKING SYSTEM

FILING FEE RECEIVED		
$1,166	FEES: Authority has been given in Paper No. _______ to charge/credit DEPOSIT ACCOUNT NO. _______________ for the following:	☐ All Fees ☐ 1.16 Fees (Filing) ☐ 1.17 Fees (Processing Ext. of time) ☐ 1.18 Fees (Issue) ☐ Other ____________ ☐ Credit

PATENT APPLICATION SERIAL NO. ______________________

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PATENT AND TRADEMARK OFFICE
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01 FC:101 231.00 CH 559.00 OP
02 FC:102 246.00 CH

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April 17, 1998

Attorney Docket No.: **09970/002001**

Box Patent Application
Assistant Commissioner for Patents
Washington, DC 20231

Presented for filing is a new original patent application of:

Applicant:	ERIC M. FOXLIN
Title:	MOTION TRACKING SYSTEM

Enclosed are the following papers, including those required to receive a filing date under 37 CFR §1.53(b):

	Pages
Specification	33
Claims	5
Abstract	1
Signed Declaration	[To Be Filed At A Later Date]
Drawings	16

This application is entitled to small entity status. A small entity statement will be filed at a later date.

Basic filing fee	395.00
Total claims in excess of 20 times $11.00	0.00
Independent claims in excess of 3 times $41.00	164.00
Fee for multiple dependent claims	0.00
Total filing fee:	$ 559.00

"EXPRESS MAIL" Mailing Label Number EM529182881US

Date of Deposit April 17, 1998

I hereby certify under 37 CFR 1.10 that this correspondence is being deposited with the United States Postal Service as **"Express Mail Post Office To Addressee"** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Lisa G Gray
Lisa G Gray

A check for the filing fee is enclosed. Please apply any other required fees or any credits to deposit account 06-1050, referencing the attorney docket number shown above.

If this application is found to be incomplete, or if a telephone conference would otherwise be helpful, please call the undersigned at 617/542-5070.

Kindly acknowledge receipt of this application by returning the enclosed postcard.

Please send all correspondence to:

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Boston, MA 02110-2804

Respectfully submitted,

Tani Robin Rohlicek Reg. No. P-43,349

David L. Feigenbaum
Reg. No. 30,378

Enclosures

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09066244 . 041798

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APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: **MOTION TRACKING SYSTEM**

APPLICANT: **ERIC M. FOXLIN**

"EXPRESS MAIL" Mailing Label Number EM529182881US

Date of Deposit April 17, 1998

I hereby certify under 37 CFR 1.10 that this correspondence is being deposited with the United States Postal Service as **"Express Mail Post Office To Addressee"** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Lisa G. Gray

Lisa G. Gray

PATENT
ATTORNEY DOCKET NO: 09970/002001

MOTION TRACKING SYSTEM

Background

The invention relates to motion tracking.

Motion tracking can use a variety of measurement modes, including inertial and acoustic measurement modes, to determine the location and orientation of a body.

Inertial motion tracking is based on measuring linear acceleration and angular velocity about a set of typically orthogonal axes. In one approach, multiple spinning gyroscopes generate forces proportional to the rates at which their spinning axes rotate in response to rotation of a tracked body to which the gyroscopes are attached. These forces are measured and used to estimate angular velocity of the body. Micro-machined vibrating elements and optical waveguide based devices may be used in place of gyroscopes.

Accelerometers generate signals proportional to forces which result from linear acceleration. In an inertial tracking system, the angular velocity and acceleration signals are integrated to determine linear velocity, linear displacement, and total angles of rotation.

As the signals generated by gyroscopic devices are noisy, the integration process results in accumulation of noise components, which is generally known as "drift". Miniaturized and low cost gyroscopic devices typically exhibit greater error. Drift rates can be as high as several degrees per second for a body at rest, and several degrees for every rotation of the body by 90 degrees. Errors in orientation estimates also affect location

estimation as the estimated orientation of the body is used to transform acceleration measurements into the fixed reference frame of the environment prior to their integration. Inaccuracy in this transformation can result a in gravity appearing as a bias ~~a~~ to resulting horizontal acceleration measurements.

One way to correct drift is to use additional sensors, such as inclinometers and a compass to occasionally or continually correct the drift of the integrated inertial measurements. For instance, U.S. Patent 5,645,077, issued to Eric M. Foxlin on July 8, 1997, discloses such an approach. This patent in incorporated herein by reference.

Another approach to motion tracking uses acoustic waves to measure distance between one or more points on a body and fixed reference points in the environment. In one arrangement, termed an "outside-in" arrangement, a set of acoustic emitters at the fixed points on the body emit pulses that are received by a set of microphones at the fixed reference points in the environment. The time of flight from an emitter to a microphone is proportional to an estimate of the distance between the emitter and the microphone (i.e., the range). The range estimates from the emitters to the respective microphones are used to triangulate the location of the emitters. The locations of multiple emitters on the body are combined to estimate the orientation of the body.

Other measurement modes, such as optical tracking of light sources on a body, can also be used to track motion of the body.

3

Summary

In one aspect, in general, the invention is a method for tracking a motion of a body which includes obtaining two types of measurements associated with the motion of the body, one of the types comprising acoustic measurement, updating an estimate of either an orientation or a position of the body based on one of the two types of measurement, for example based on inertial measurement, and updating the estimate based on the other of the two types of measurements, for example based on acoustic ranging.

In another aspect, in general, the invention is a method for tracking the motion of a body including selecting one of a set of reference devices, transmitting a control signal to the selected reference device, for example by a transmitting a wireless control signal, receiving ~~an~~ a range measurement signal from the reference device, accepting a range measurement related to a distance to the selected reference device, and updating a location estimate or an orientation estimate of the body using the accepted range measurement. The method can further include determining a range measurement based on a time of flight of the range measurement signal.

Advantages of the invention include providing a 6-degree-of-freedom tracking capability that can function over an essentially unlimited space in which an expandable constellation of ultrasonic beacons is installed. Inertial measurements provide smooth and responsive sensing of motion while the ultrasonic measurements provide ongoing correction of errors, such as those caused by drift of the inertial

tracking component of the system. Small and inexpensive inertial sensors, which often exhibit relatively large drift, can be used while still providing an overall system without unbounded drift. Small, lightweight inertial sensors are well suited for head mounted tracking for virtual or augmented reality display systems. By correcting drift using ultrasonic measurements, drift correction measurements which may be sensitive to external factors such as magnetic field variations, are not needed. The constellation of ultrasonic beacons can be easily expanded as each beacon functions independently and there is no need for wiring among the beacons. The tracking device only relies on use of a small number of ultrasonic beacons at any time, thereby allowing the space in which the tracking device operates to have irregular regions, such as multiple rooms in a building.

Another advantage of the invention is that by using an "inside-out" configuration, there is no latency in acoustic range measurements due to motion of the body after an acoustic wave is emitted.

Yet another advantage of the invention is that tracking continues using inertial measurements even when acoustic measurements cannot be made, for example, due to occlusion of the beacons. Drift in the inertial tracking is then corrected once acoustic measurements can once again be made.

In yet another advantage, the invention provides line-of-sight redundancy whereby one or more paths between a emitters and sensors can be ~~block~~ blocked while still allowing

tracking of a body.

Other features and advantages of the invention will be apparent from the following description, and from the claims.

Description of the Drawings

Fig. 1 shows a tracking device and a constellation of acoustic beacons used for tracking the device;

Fig. 2 shows components of a tracking device processor;

Fig. 3 illustrates a combined inertial and acoustic tracking approach;

Fig. 4 shows an inertial measurement unit (IMU);

Fig. 5 shows an ultrasonic range measurement unit (URM) and an ultrasonic beacon;

Fig. 6 shows an input/output interface used in a tracking device processor to interface with inertial and ultrasonic measurement units;

Fig. 7a illustrates the navigation and body frames of reference;

Fig. 7b illustrates mutual tracking devices;

Fig. 8 is a signal flow diagram of an inertial tracker;

Fig. 9 is a signal flow diagram of an ultrasonic range measurement subsystem;

Fig. 10 is a signal flow diagram of a tracking device including an inertial tracker and Kalman predictor and updater elements;

Fig. 11 is a signal flow diagram of a Kalman predictor;

6

Fig. 12 is a signal flow diagram of a Kalman updater;

Fig. 13 is a flowchart of a tracking procedure;

Fig. 14a illustrates tracking of a second body relative to a first tracked body;

Fig. 14b illustrates mutual tracking of multiple devices;

Fig. 15 illustrates head mounted display system;

Fig. 16 illustrates a camera tracking system for television; and

Fig. 17 illustrates tracking of bodies in an automobile.

Description

Referring to Fig. 1, a tracking device 100 which maintains an estimate of its location and orientation is free to move within a large room. For example, tracking device 100 can be fixed to a head-up display (HUD) on an operator's head, and tracking device 100 moves through the room, and changes orientation, as the operator moves and orients his head. Tracking device 100 includes a processor 130 coupled to an inertial measurement unit (IMU) 140 which provides inertial measurements related to linear acceleration and to rates of rotation. Processor 130 uses the inertial measurements to determine motion of tracking device 100 as it moves through the room.

Processor 130 is also coupled to an array of three ultrasonic range measurement units (URM) 110 which are used to receive acoustic signals sent from an ultrasonic beacon array 120, a "constellation" of beacons. Ultrasonic beacon

array 120 includes independent ultrasonic beacons 122 in fixed locations in the environment, for example, arranged on the ceiling of the large room in a regular pattern such as on a grid with 2 foot spacing. Processor 130 uses the signals from particular ultrasonic beacons 122, as well as known three-dimensional locations of those beacons, to estimate the range to those beacons and thereby sense motion for tracking device 100. Each ultrasonic beacon 122 sends an ultrasonic pulse 114 in response to infra-red command signal 112 sent from tracking device 100. In particular, each URM 110 on tracking device 100 broadcasts infra-red (IR) signals to all of the ultrasonic beacons 122. These IR signals include address information so that only one beacon, or a small number of beacons, recognize each IR signal as intended for it, and responds to the signal. In response to an IR signal, an addressed beacon immediately broadcasts an ultrasonic pulse that is then received by one or more URM 110. As processor 130 knows that the addressed beacon responded immediately to the IR command, it determines the time of flight by measuring the delay from issuing the IR command to detecting the ultrasonic pulse. The time of flight of the ultrasonic pulse is used to estimate the range to the beacon, which is then used to update the position and orientation of tracking device 100.

Both the inertial measurements and the ultrasonic signal based measurements have limitations. Relying on either mode of measurement individually is not as accurate as combining the measurements. Tracking device 100 combines measurements from both measurement modes and adjusts its

8

estimate of position and orientation (i.e., 6 degrees of freedom, "6-DOF") to reflect measurements from both modes as they are available, or after some delay. To do this, processor 130 hosts an implementation of an extended Kalman filter (EKF) that is used to combine the measurements and maintain ongoing estimates of location and orientation of tracking device 100, as well as to maintain an estimate of the uncertainty in those estimates.

Referring to Fig. 2, processor 130 includes a central processing unit (CPU) 200, such as an Intel 80486 microprocessor, program storage 220, such as read-only memory (ROM), and working storage 230, such as dynamic random-access memory (RAM). CPU 200 is also coupled to an input/output interface 210 which provide an interface to IMU 140 and the URM 110. Input/output interface 210 includes digital logic that provides digital interfaces to IMU 140 and the URM 110.

IMU 140 provides a serial data stream 201 encoding inertial measurements. Input/output interface 210 converts this serial data to a parallel form 212 for transfer to CPU 200. Each URM 110 accepts a serial signal 211 that is used to drive an IR light emitting diode 510 to broadcast the IR control signals to ultrasonic beacons 122 (Fig. 1). Input/output interface 210 accepts address information from CPU 200 identifying one or more ultrasonic beacons and provides the serial signal to each of the URM 110 which then impose the serial signal on an IR transmission (e.g., by amplitude modulation). The same serial signal is provided to all the URMs 110, which concurrently broadcast the same

9

IR signal. Each URM 110 provides in return a logical signal 202 to input/output interface 210 indicating arrivals of ultrasonic pulses. Input/output interface 210 includes timers that determine the time of flight of ultrasonic pulses from the beacons, and thereby determines range estimates to the beacons. These range estimates are provided to CPU 200.

An implementation of a tracking algorithm is stored in program storage 220 and executed by CPU 200 to convert the measurements obtained from input/output interface 210 into position and orientation estimates. CPU 200 is also coupled to fixed data storage 240, which includes information such as a predetermined map of the locations of the ultrasonic beacons, and the locations of the microphones of the URM 110. Processor 130 also includes a communication interface 260 for coupling CPU 200 with other devices, such as a display device 280 that modifies its display based on the position and orientation of tracking device 100.

Operation of the system can be understood by referring to Fig. 3, a two-dimensional view of the room shown in Fig. 1 (from above). The sequence of open circles and arrows 310a-e represent the actual location and orientation of tracking device 100 at each of a sequence of time steps. Based on prior measurements, and on inertial measurements at the first time step, filled circle and arrow 312a represent the estimate by tracking device 100 of the location and orientation of the tracking device at the first time step. At the next time step, tracking device 100 moves to position 310b, and based on a new inertial measurement,

10

tracking device 100 updates its position estimate to 312b. This is repeated for the next time step with actual position 310c and estimated position 312c.

After reaching position 310b, tracking device 100 sends an IR command addressed to one of the ultrasonic transducers 122, illustrated by dotted line 320. After receiving the IR command (with essentially no delay), ultrasonic transducer 122 transmits an ultrasonic pulse, illustrated by wave 324. Wave 324 reaches tracking device 100 some time later, at actual location 330. Based on the time of arrival, tracking device 100 estimates that it was at position 332 when wave 326 reached it.

At the next time step, tracking device 100 first estimates its position 312d based on an inertial measurement. Using range information related to the separation of the location of ultrasonic transducer 122 and location 332 and a measured time of flight of the ultrasonic wave, tracking device 100 computes a refined position estimate 312d'. The process repeats using inertial measurements at true position 310e and estimated position 312e.

In general, both an inertial measurement and an ultrasonic measurement can be used at each time step, although ultrasonic measurement can be made less frequently. At each time step, both location and orientation (attitude) is updated. The ultrasonic pulses can provide information related to both location and orientation through the use of multiple microphones that are displaced relative to one another.

Referring to Fig. 4, inertial measurement unit (IMU) 140 includes three angular rate sensors (e.g., micro-machined vibrating rotation sensors or small rotating gyroscopes) 420a-c, and three linear acceleration sensors 410a-c. The sensors are arranged to lie along three orthogonal axes that remain fixed in the frame of reference of tracking device 100. Each acceleration sensor provides a signal that is generally proportional to the acceleration along the corresponding axis, and each angular rate sensor provides a signal that is generally proportional to the rate of rotation about the corresponding axis.

As the orientation of inertial measurement unit 140 changes, the signals such as the acceleration signals correspond to changing directions in the fixed (navigation) reference frame of the room. Inertial measurement unit 140 also includes a signal interface 430 which accepts the signals 411 from each of the six accelerometers and angular rate sensors, and transmits a serial data stream 413 which multiplexes digital representations of the acceleration and angular rate signals. As is discussed further below, the acceleration and angular rate signals are imperfect, and may exhibit additive bias and scaling inaccuracies. These scaling and bias inaccuracies may depend on the motion of the device.

Referring to Fig. 5, each ultrasonic measurement unit 110 includes an infra-red (IR) light-emitting diode (LED) 510 that is driven by IR signal generator 512. Signal generator 512 accepts serial signal 211 from input/output interface 210 (Fig. 2) and drives IR LED 510 to transmit

12

that signal to one or more ultrasonic beacon 122. The address of an ultrasonic beacon to which a range is desired is encoded in serial signal 211. Each ultrasonic beacon 122 includes an IR sensor 540 which, if there is a sufficiently short unobstructed path between ultrasonic range measurement unit 110 and that ultrasonic beacon, receives the IR signal which is then decoded by IR signal decoder 542. This decoded signal includes the address information transmitted by the ultrasonic range measurement unit. Control circuitry 560 receives the decoded IR signal, and determines whether that ultrasonic beacon is indeed being addressed, and if so, signals a pulse generator 552 to provide a signal to an ultrasonic transducer 550 which generates an ultrasonic pulse. The pulse passes through the air to ultrasonic range measurement unit 110 where a microphone 520 receives the ultrasonic pulse and passes a corresponding electrical signal to a pulse detector 522 which produces a logical signal indicating arrival of the pulse. This pulse detection signal is passed to input/output interface 210 (Fig. 2). As discussed below, the time of flight is not a perfectly accurate measurement of range. Error sources include timing errors in detection of the pulse, acoustic propagation rate variations, for example due to air temperature or air flow, and non-uniform in different directions propagation of the ultrasonic wave from the ultrasonic beacon.

Input/output interface 210 includes circuitry (i.e., a programmable logic array) which implements logical components shown in Fig. 6. An IMU data buffer 630 accepts

serially encoded acceleration and angular rate data 413 from IMU 140, and provides the six acceleration and rotation measurements 631 as output to CPU 200. Input/output interface 210 also includes a beacon address buffer 610. CPU 200 (Fig. 2) provides an address of the ultrasonic beacon to which a range should be measured. Beacon address buffer 610 stores the address and provides that address in serial form to each of the URMs 110. At the same time that the address is transmitted by each of the URM 110 (and received by the ultrasonic beacons 122), three counters 620a-c are reset and begin incrementing from zero at a fixed clocking rate (e.g., 2 MHz). When each URM 110 detects the ultrasonic pulse from the beacon, the corresponding pulse detection signal is passed to the corresponding counter which stops counting. The counts are then available to CPU 200 as the measurements of the time of flight of the ultrasonic pulse from the ultrasonic beacon to each URM 110.

Referring to Figs. 7a-b, tracking device 100 (Fig. 1) determines its location in the navigation reference frame of the room, shown as axes 710, labeled N (north), E (east), and D (down). Location $\underline{r}^{(n)}$ 730 is a vector with components $(r_N^{(n)}, r_E^{(n)}, r_D^{(n)})^T$ of the displacement from axes 710 in the N, E, and D directions respectively. Tracking device 100 also determines its attitude (orientation).

Referring to Fig. 7b, attitude is represented in terms of the roll, pitch, and yaw (Euler) angles, $\underline{\theta} = (\psi, \theta, \phi)^T$, needed to align the body attitude, represented by coordinate axes 720, with the navigation attitude represented by coordinate axes 710. The three

Euler angles are represented as a 3x3 direction cosine matrix, $C_b^n(\underline{\theta})$, which transforms a vector of coordinates in the body frame of reference by essentially applying in sequence yaw, pitch, and then roll motions around the z, y, and then x axes. The direction cosine matrix can be defined as

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$$C(\underline{\theta}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The superscript and subscript notation C_b^n signifies that the matrix takes a vector in the "b" (body) reference frame and provides a vector in the "n" (navigation) reference frame.

Referring to Fig. 8, inertial sensors 800, including rotation sensors 420a-c and acceleration sensors 410a-c, provide inertial measurement signals to an inertial tracker 810. Inertial tracker 810 implements a discrete time approximation of the signal flow shown in the Fig. 8. Inertial tracker 810 includes several stages. First, gyroscope compensation 820 modifies the (vector) angular rate signal $\underline{\omega}$ to account for bias in the measurement. In this example, only an additive bias $\underline{\delta\omega}$ is corrected. Other biases such as a multiplicative error (e.g., an incorrect scale factor), and errors due to mounting inaccuracies can be corrected as well. Accelerometer compensation 830 similarly corrects for an additive bias $\underline{\delta a}^{(b)}$ on the acceleration signals $\underline{a}^{(b)}$. As is discussed fully below,

15

several parameters, including the bias terms $\underline{\delta\omega}$ and $\underline{\delta a}^{(b)}$, are estimated using ultrasonic measurements.

Attitude integration 840 updates the attitude estimate based on the bias corrected rotation signal. In this example, attitude integration is performed using a direction cosine representation of the attitude. A discrete time implementation of the continuous differential equation $\dot{C}_b^n(t) = C_b^n(t)\, S(\underline{\omega}(t))$ is used to update the direction cosine matrix at a fixed rate, typically between 100 and 200 per second. Changing notation to a discrete time system (e.g., $C_k = C_b^n(k\Delta t)$), the discrete time update of the direction cosine matrix is implemented as

$$C_k = C_{k-1}\left(I + \frac{\sin\,\delta\theta}{\delta\theta} S(\underline{\delta\theta}) + \frac{1-\cos\,\delta\theta}{\delta\theta^2} S(\underline{\delta\theta})^2 \right)$$

where

$$\underline{\delta\theta} = \frac{\underline{\omega}_{k-1} + \underline{\omega}_k}{2} \Delta t\,, \quad \delta\theta = \|\underline{\delta\theta}\|$$

and

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$$S(\underline{\delta\theta}) = \begin{bmatrix} 0 & -\delta\theta_z & \delta\theta_y \\ \delta\theta_z & 0 & -\delta\theta_x \\ -\delta\theta_y & \delta\theta_x & 0 \end{bmatrix}$$

is the skew symmetric matrix of $\underline{\delta\theta}$. Note that $S(\underline{\delta\Theta})$ satisfies

$$S(\underline{\delta\theta})^2 = \delta\theta^2\, I - \underline{\delta\theta}\; \underline{\delta\theta}^T \,.$$

In order to ensure that C_k truly is a direction cosine matrix, its rows are orthonormalized after each iteration to

16

remove any numerical or approximation errors that may have entered into its entries.

Based on the tracked direction cosine matrix C_k, coordinate transformation 850 accepts the bias corrected acceleration signal in the body reference frame and outputs an acceleration signal in the navigation reference frame according to

$$\underline{a}_k^{(n)} = C_k\,(\underline{\tilde{a}}_k^{(b)} - \delta\underline{a}_k^{(b)}) + (0,0,-g)^T .$$

a Double integration ~~850~~ 860 then computes the velocity and position according to

$$\underline{v}_k^{(n)} = \underline{v}_{k-1}^{(n)} + \frac{\underline{a}_{k-1}^{(n)} + \underline{a}_k^{(n)}}{2}\Delta t ,$$

and

$$\underline{r}_k^{(n)} = \underline{r}_{k-1}^{(n)} + \underline{v}_{k-1}^{(n)}\Delta t + \frac{2\underline{a}_{k-1}^{(n)} + \underline{a}_k^{(n)}}{6}\Delta t^2 .$$

Euler angle computation 870 takes the direction cosine matrix and outputs the corresponding Euler angles. The output of inertial tracker 810 is $(\underline{\theta}, \underline{r}^{(n)})^T$. The state of the inertial tracker includes a 15-dimensional vector composed on five sets of three-dimensional values

$$\underline{x} = (\underline{\theta}, \underline{\omega}, \underline{r}^{(n)}, \underline{v}^{(n)}, \underline{a}^{(n)})^T .$$

As is discussed fully below, inertial tracker 810 receives error update signals $\delta\underline{x}$ derived from ultrasonic range measurements that it uses to correct the attitude, velocity, and position values, and to update the parameters

of the gyroscope and accelerometer bias correction elements.

Referring to Fig. 9, a beacon sequencer 910 receives location estimates $\underline{r}^{(n)}$ from inertial tracker 810. Using a beacon map 915 of the locations (and addresses) of the ultrasonic beacons 122 (shown in Fig. 1), beacon sequencer 910 determines which beacon to trigger at each time step in order to generate ultrasonic range measurements. For instance, beacon sequencer 910 determines the closest beacons to the current location, and cycles among these beacons on each time step. As the location estimate changes, the set of closest beacons also, in general, changes. After beacon sequencer 910 triggers each of the beacons in turn, the corresponding ultrasonic pulses arrive and are detected by the tracking device. Each pulse generates one range measurement for each microphone used to detect the pulse. In this embodiment, each pulse generates a set of three range measurements, one from each of the microphones in the three URM 110.

Referring still to Fig. 9, range measurement 920 corresponds to the process of receiving an ultrasonic range estimate. The relevant parameters for a range measurement are the location of the addressed beacon, $\underline{b}^{(n)}$, the location of the microphone used to detect the pulse, $\underline{m}^{(b)}$, the range estimate itself, d_r, and the time the pulse was detected, t_r, which is used to correct for latency in the measurements. Note that if the location estimate had no error, and the range estimate was perfectly accurate, then the range estimate would satisfy

18

$$d_r = \| \underline{b}^{(n)} - (\underline{r}^{(n)}(t_r) + C_b^{\,n}(t_r)\underline{m}^{(b)}) \| \quad .$$

Deviations from this equality are used to correct the parameters and outputs of inertial tracker 810.

A complementary Kalman filter is used by tracking device 100 to improve the tracked location and orientation estimate by incrementally updating the tracked quantities as the range measurements come in. Referring to Fig. 10, the approach involves two related components. As inertial tracker 810 updates its output $\underline{x}$, a Kalman predictor 1010 maintains an estimated covariance matrix P of the error in $\underline{x}$. For instance, in the absence of any drift compensation in inertial tracker 810, the covariance matrix P would correspond to an ever increasing error.

The second component used in this approach is a Kalman updater 1020 which accepts information from range measurement 920 and using this measurement information determines an estimate of the accumulated error $\underline{\delta x}$ which it feeds back to inertial tracker 810 where it is used to update $\underline{x}$. Also, after each ultrasonic measurement, Kalman updater 1020 computes a new estimated covariance matrix $P(+)$ of the error in $\underline{x}$ after the update, which it feeds back to Kalman predictor 1010. Each ultrasonic measurement partially corrects the output of inertial tracker 810. A continuous series of ultrasonic updates ensures that the error remains small.

Inertial tracker 810 is a nonlinear processor of its inputs, and therefore, a formulation of a Kalman filter for a purely linear filter driven by Gaussian noise is not

appropriate. Using what is generally known as an "extended Kalman filter" (EKF), a linearized dynamical system model which characterizes the propagation of error in the output $\underline{x}$ of inertial tracker 810 is used. The error that the EKF models is

$$\underline{\delta x} = (\underline{\phi}\,,\ \underline{\delta\omega}^{(b)}\,,\ \underline{\delta r}^{(n)}\,,\ \underline{\delta v}^{(n)}\,,\ \underline{\delta a}^{(b)})^T$$

with the components corresponding to the components of the vector output of the inertial tracker. Note that the error term $\underline{\delta a}^{(b)}$ is modeled in the body coordinate system rather than in the navigation coordinate system, and that the other elements correspond directly to errors in the output of inertial tracker 810. The parameters of the linearized error propagation model include a state transition matrix, and a covariance matrix of a driving noise which is assumed to drive this error model. Both the state transition matrix and the driving noise covariance depend on the output of inertial tracker. In the absence of any measurements, the mean of the error process remains zero. However, the covariance of the error grows. The linearized model of error propagation is

$$\underline{\delta x}_k = F(\underline{x}_{k-1})\ \underline{\delta x}_{k-1} + \underline{w}_{k-1}\ .$$

The entries of $F_k = F(\underline{x}_{k-1})$ are derived from a perturbation analysis of the update equations used in inertial tracker 810, and correspond to the following error propagation equations:

20

$$\underline{\phi}_k = \underline{\phi}_{k-1} - C_b^n\, \underline{\delta\omega}_{k-1} \;,$$
$$\underline{\delta\omega}_k = \underline{\delta\omega}_{k-1} \;,$$
$$\underline{\delta r}_k = \underline{\delta r}_{k-1} + \Delta t\, \underline{\delta v}_{k-1} - \frac{1}{2}\Delta t^2 \left(C_b^n\, \underline{\delta a}^{(b)}_{k-1} - S(\underline{\phi}_{k-1})(\underline{a}^{(n)}_{k-1} + (0,0,-g)^T) \right)$$
$$\underline{\delta v}_k = \underline{\delta v}_{k-1} + \Delta t\, \underline{\delta a}^{(b)}_{k-1} - \Delta t\, S(\underline{\phi}_{k-1})(\underline{a}^{(n)}_{k-1} + (0,0,-g)^T) \;, \text{ and}$$
$$\underline{\delta a}^{(b)}_k = \underline{\delta a}^{(b)}_{k-1} \;.$$

The covariance Q_k of the process noise w_k is assumed to be diagonal. The entries of this covariance matrix are derived from known sources of error in the inertial measurements provided to inertial tracker 810, including additive bias errors, scaling errors, alignment errors of the sensors with the body axes, and signal noise from the sensors themselves. The individual variances depend on the output of the inertial tracker as follows:

$$Q_k = \mathrm{diag}\left(\sigma^2_{\phi_x}, \sigma^2_{\phi_y}, \sigma^2_{\phi_z}, \sigma^2_{\omega}, \sigma^2_{\omega}, \sigma^2_{\omega}, \sigma^2_{r_x}, \sigma^2_{r_y}, \sigma^2_{r_z}, \sigma^2_{v_x}, \sigma^2_{v_y}, \sigma^2_{v_z}, \sigma^2_{a}, \sigma^2_{a}, \sigma^2_{a} \right)$$

where the individual variance terms are parameterized as follows:

$$\sigma_{\phi_x} = \mathrm{GyroScale}\ \omega_x\ \Delta t + \mathrm{GyroAlign}\ (\omega_y + \omega_z)\ \Delta t + \mathrm{GyroNoise}\ \sqrt{\Delta t}$$
$$\sigma_{\phi_y} = \mathrm{GyroScale}\ \omega_y\ \Delta t + \mathrm{GyroAlign}\ (\omega_x + \omega_z)\ \Delta t + \mathrm{GyroNoise}\ \sqrt{\Delta t}$$
$$\sigma_{\phi_z} = \mathrm{GyroScale}\ \omega_z\ \Delta t + \mathrm{GyroAlign}\ (\omega_x + \omega_y)\ \Delta t + \mathrm{GyroNoise}\ \sqrt{\Delta t}$$
$$\sigma_{\omega} = \mathrm{GyroBiasChangeRate}\ \Delta t$$
$$\sigma_{r_x} = \sigma_{r_y} = \sigma_{r_z} = 0$$
$$\sigma_{v_x} = \mathrm{AccelScale}\ a_x\ \Delta t + \mathrm{AccelAlign}\ (a_y + a_z)\ \Delta t + \mathrm{AccelNoise}\ \sqrt{\Delta t}$$
$$\sigma_{v_y} = \mathrm{AccelScale}\ a_y\ \Delta t + \mathrm{AccelAlign}\ (a_x + a_z)\ \Delta t + \mathrm{AccelNoise}\ \sqrt{\Delta t}$$
$$\sigma_{v_z} = \mathrm{AccelScale}\ a_z\ \Delta t + \mathrm{AccelAlign}\ (a_x + a_y)\ \Delta t + \mathrm{AccelNoise}\ \sqrt{\Delta t}$$
$$\sigma^2_a = \mathrm{AccelBiasChangeRate}\ \Delta t$$

where GyroScale, AccelScale, GyroAlign, and AccelAlign correspond to degree of uncertainty in calibration coefficients used for instrument error compensation. In general, a non-diagonal process noise covariance can be used.

Referring to Fig. 11, Kalman predictor 1010 has two stages. An error linearization stage 1110 first computes F_k and Q_k as outlined above. Then, a covariance propagation stage 1120 iteratively updates the error covariance by applying a Kalman filter covariance propagation equation

$$P_k = F_{k-1} P_{k-1} F_{k-1}^T + Q_k$$

on each time step. When Kalman predictor 1010 receives an updated covariance $P(+)$, which is produced as a result of an ultrasonic range measurement, that updated covariance replaces the current error covariance P.

Referring to Fig. 12, Kalman updater 1020 accepts the output of range measurement 920, as well as the estimate of location and orientation from inertial tracker 810, and the covariance of the error of the estimate of location and orientation from Kalman predictor 1010, and computes an error estimate, and an updated covariance that results from applying the error estimate. A first stage of Kalman updater 1020 is measurement residual computation 1210. The difference between the expected range and the measured range is computed as

22

$$\delta d_r = d_r - \| \underline{b}^{(n)} - (\underline{r}^{(n)}(t_r) + C_b^{\,n}(t_r)\underline{m}^{(b)}) \| \;.$$

Note that in general a range measurement is used some time after it was initially detected. In order to account for this latency, estimates of the location and orientation of the tracking device at the time that the acoustic pulse arrived are used rather than the location and orientation at the time that the measurement is used. The current location, orientation, and linear and angular rate estimates are used to extrapolate back to the measurement time to determine $\underline{r}^{(n)}(t_r)$ and $C_b^{\,n}(t_r)$.

In order to apply the Kalman update equations, this residual is modeled using a linearized observation equation as

$$\delta d_r = H(\underline{x},\underline{b},d_r,\underline{m})\ \underline{\delta x} + \nu \;.$$

The observation matrix $H_k = H(\underline{x}_k,\underline{b},d_r,\underline{m})$ is the linear effect of errors in location and orientation on the error in range measurement. The additive noise ν has a variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$. H_k has the form

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$$H_k = \Big(\frac{b_D m_E - b_E m_D + r_E m_N - r_D m_E}{d_r}, \frac{b_N m_D - b_D m_N + r_D m_N - r_N m_D}{d_r}, \frac{b_E m_N - b_N m_E + r_N m_E - r_E m_N}{d_r},$$
$$0,0,0,\frac{r_N + m_N - b_N}{d_r}, \frac{r_E + m_E - b_E}{d_r}, \frac{r_D + m_D - b_D}{d_r},0,0,0,0,0,0\Big)$$

The variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$ is derived to model various phenomena associated with ultrasonic range measurement. For example, as the range increases, pulse detection is more difficult,

due in part to pulse spreading, and an increased variance is used to model the associated range measurement error. The variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$ has the form

$$R = \sigma_u^2 + \sigma_l^2$$

and is parameterized as

$$\sigma_u^2 = \text{NoiseFloor} + \text{NoiseScale}\ d_r$$

and

$$\sigma_l^2 = (k\Delta t - t_r)\ H_k\left(\omega_x,\omega_y,\omega_z,0,0,0,v_x,v_y,v_z,0,0,0,0,0,0\right)^T$$

The first two terms of H_k can alternatively be set to zero to allow accelerometric tilt correction (if it is more accurate). It the third term is set to zero, yaw drift correction will occur over a longer time period but to higher accuracy.

Kalman updater 1020 includes a measurement accept/reject stage 1230. Accept/reject stage 1230 takes the measurement residual, $\underline{\delta x}$, and the computed variance, R , of the measurement residual. If the measurement residual is greater in magnitude than a predetermined multiple of the computed standard deviation of the measurement residual, then the measurement is rejected as being suspect, for example, due to premature or late triggering of an ultrasonic pulse detector. Otherwise the measurement residual is further processed to compute the state error estimate, $\underline{\delta x}$. Using Kalman filter update equations, Kalman gain computation 1240 computes the Kalman gain as

$$K = P_k H_k^T \left(H_k P_k H_k^T + R \right)^{-1} .$$

Error estimator 1250 then computes the error estimate as $\underline{\delta x} = K\,\delta d$, and covariance updater 1260 computes the updated error covariance as

$$P(+) = \left(I - K H \right) P_k .$$

The components of $\underline{\delta x}$ are then used to update inertial tracker 810. The computed terms $\underline{\delta\omega}$ and $\underline{\delta a}^{(b)}$ are passed to gyroscope bias correction 820 and accelerometer bias correction 830 (Fig. 8), respectively, where they are added to the current stored bias parameters. The computed terms $\underline{\delta v}^{(n)}$ and $\underline{\delta r}^{(n)}$ are passed to double integration 860 (Fig. 8) where they are added to the current estimates of $\underline{v}^{(n)}$ and $\underline{r}^{(n)}$, respectively. Finally, the direction cosine matrix is updated according to

$$C_k \leftarrow \left(I - S(\underline{\phi}) \right) C_k$$

and re-orthonormalized.

Referring back to Fig. 1, ultrasonic beacon array 120 includes individual ultrasonic beacons 122 arranged in a regular pattern. For example, the beacons may be arranged on a square grid with a spacing of approximately 2 feet, preferably with an accuracy of 3mm or less. A limited number of addresses are available for the beacons, in this embodiment only eight different addresses are available due to hardware limitations. Therefore, when the tracking

device sends an IR command to an address, in general, multiple ultrasonic beacons will receive the signal and respond. Only the closest beacon with any particular address is used for range measurement. However, as multiple beacons may be responding to each IR command, the pulse detection circuit may be triggered prematurely, for example, by a pulse from a beacon triggered in a previous iteration, but that is sufficiently far away that its pulse does not arrive until after a subsequent iteration. In order to avoid this pre-triggering problem, pulse detector 522 (Fig. 5) is only enabled during a time window about the ~~expect~~ expected time the desired pulse would arrive. This avoids false triggering by pulses from other beacons, or signals resulting from long time constant reverberation of previous pulses.

In the description the tracking and Kalman updating procedures, an initial location and orientation estimate is assumed to be known. This is not necessarily the case and an automatic acquisition algorithm is used by tracking device 100. The limited number of addresses of ultrasonic beacons is used as the basis for an initial acquisition algorithm. Initially, the tracking device triggers beacons with each of the allowable addresses and measures the range to the closest beacon of each address. Then, the addresses of the four closest beacons are determined from the range measurements. The tracking unit includes a beacon map that includes the locations and addresses of all the beacons. The beacons are arranged such that the addresses of the four closest beacons limit the possible locations to a small

portion of the room. If there is ambiguity based on the closest beacons, the actual distances to the beacons are used in a triangulation procedure to resolve the ambiguity. The initial orientation is based on the relative range measurements to each of the microphones.

The overall tracking procedure can be summarized by the flowchart shown in Fig. 13. First, the initial location and orientation is acquired (step 1310) using the approach outlined above. The procedure then enters a loop that is executed once each time step. After waiting for the next time step (step 1320), inertial measurements are received (step 1330) and the tracked variables, $\underline{x}$, and the error covariance, P , are updated using the inertial measurements (step 1340). If an ultrasonic range measurement that has not yet been processed is available (step 1350), that range measurement is used to compute an error update, $\underline{\delta x}$, and updated error covariance, $P(+)$, (step 1360). The error update and new error covariance are then used to update the inertial tracker and the Kalman predictor (step 1370). The procedure then involves determining whether further range measurements must be commanded at this time step (step 1380). As three range measurements are made for each pulse but only one range measurement is used per time step, there may be a backlog of range measurements that will be applied in the upcoming time steps. Therefore, a new range measurement may not be necessarily for several future time steps. Taking into account the expected time of flight of the next ultrasonic pulse (which in general is more than a single time step), the procedure determines if an IR command

27

should be sent to a beacon at this time step (step 1380), the next beacon address is selected (step 1390) and, if so, the IR command to that beacon is sent (step 1395). The procedure then loops again starting at step 1320, waiting for the start of the next time interval.

Several alternative approaches can also be used. In the described embodiment, only one range measurement is used per time step. Alternatively, all available range measurements can be used at each time step if the processor 130 has sufficient computation capacity. This alternative approach is implemented by looping from step 1370 back to step 1350 until all the range measurements are accounted for. Alternatively, rather than applying the Kalman updates for each of the scalar range measurements in turn, all can be applied in a single step using similar update equations for vector observations and correlated observation noise. Also, rather than deferring processing of a range measurement until the next time step, the range measurements can be incorporated as they arrive, and not synchronized with the inertial tracker updates.

The procedure described above can be combined with other measurement modes. For example, inclinometers can be used to provide measurements to the extended Kalman filter that allow correction of attitude drift. Also, rather than using three or more microphones which allow correction of all three degrees of rotation, two microphones can be used for range measurement in combination with a measurement mode such as inclinometers. In this way, some drift correction can be based on inclinometers, but a compass, which is

28

sensitive to magnetic field variations, is not needed for drift correction. Many more than three microphones can also be used to provide greater redundancy and allow more rotation freedom.

As an alternative to mounting beacons in fixed locations in the environment, and microphones on the tracking device, which is often referred to as an "inside-out" arrangement, this could be reversed in an "outside-in" arrangement. The tracking device then provides the ultrasonic pulses and a coordinated array of microphones senses the location of the tracking device. Note that by the time a pulse has reached a microphone, the tracking device will have, in general, moved on to a new location. This latency of measurements must be compensated for in a manner similar to the compensation of latency in use of range measurements described above.

Beacons 122 need not be mounted in a planar array. They could be mounted on walls as well as on the ceiling, or on other supports in the environment. For example, the beacons can be mounted on light fixtures. The number of beacons can be chosen to match the user's requirements, and the locations of the beacons can be chosen based on a variety of criterea, such as availability of suitable mounting points and geometric considerations, and the beacon map can be set to match the chosen number and locations of the beacons. The number of beacons in the constellation can be ~~increase~~ increased or reduced by the user, so long as the beacon map remains up to date.

The command signals from the tracking device to the

beacons can be sent using other modes than IR transmission. For example, RF, visible, or acoustic signals can be used. The tracking device can also be wired to the beacons.

Two or more objects can be tracked in an "inside-outside-in" arrangement. Referring to Fig. 14a, tracking device 100 tracks its location as before. A second tracking device 1400 includes three addressable ultrasonic beacons 1410 arranged in a known relationship to one another. By triggering beacons 1410 to transmit acoustic pulses that are received at the URM 110 on tracking device 100, tracking device can determine the relative location and orientation of the second tracking device. A further extension, which provides increased accuracy in the relative location and orientation estimates involves having a second inertial measurement unit fixed to tracking device 1400, and transmitting its inertial measurements to tracking device 100. If only a single beacon is placed on the second object, the relative location can be sensed using ultrasonic range measurements, without necessarily tracking the relative orientation of the second device.

Referring to Fig. 14b, a "mutual tracking network" made up of multiple tracking devices can be used. These tracking devices track their individual locations with respect to the locations of the other devices in the environment, including fixed beacons and other moving tracked objects. This can be done with an ~~addition~~ additional communication system coupling the tracking devices, such as an RF local area network.

In the above described embodiments, the "map" of the

30

beacon array is assumed to be accurate. As the range measurements include redundant information, errors in placement of the beacons can be iteratively estimated and updated, thereby improving accuracy. Specifically, the placement errors of the beacons can be included in the state of the extended Kalman filter, and range measurements from each beacon would then contribute over time to estimating the placement errors. A separate initial automatic "mapping" mode can also be used in which, through range measurement from one or more locations in the room and triangulation calculations, the locations of the beacons can be determined. These automatically determined locations can be used as the known locations, or as initial estimates that are then further updated using the Kalman filter. In this type of approach, the beacons can be irregularly placed within the room without requiring that they be precisely positioned.

The tracking approach described above has several applications. A first application involves coupling the tracking device to a head mounted display. Referring to Fig. 15, a head mounted display 1510, allows a user to directly view a physical object 1520, such as a work piece. Display 1510, using the known location of work piece 1520 in the frame of reference of the room, superimposes information on the user's view of the work piece. For example, applying wiring harnesses to a large device, the superimposed information can include information related to the correct placement of the wiring harnesses. A similar head mounted display can also be used to provide the complete image

viewed by a user in a virtual reality system, rather than superimposing an image on the real view seen by the user.

Another application involves tracking a camera location in a television application. Referring to Fig. 16, a common technique in television production is to film a subject 1620 in front of a blank (typically monochrome) background and then to electronically superimpose another image (illustrated as 1630) as a background. A difficulty with such a technique is that as camera 1610 moves, the background image should change to reflect the camera's motion. By attaching tracking device 100 to camera 1610, the location and orientation of the camera is tracked and the background image can be automatically modified by an image processor that receives the changing position and orientation of the camera. This approach allows a construction of large "virtual sets" which ~~is~~ are stored in the image processor, and thereby multiple and changing camera "angles" can be used.

Another application involves sensing of motion of elements in an automobile, for example, in an automotive crash test. Referring to Fig. 17, the motion of a dummy 1720 within a crashing automobile 1710 can be tracked using tracking device 100. In addition, a second object, such as a point on the firewall can be tracked using an addition beacon 1730 using the inside-outside-in approach described above. This allows both tracking of the dummy in the reference frame of the automobile, and tracking of a point within the vehicle relative to the dummy.

Other applications include robotic navigation,

tracking of inventory, assets, or personnel, shipboard virtual or augmented reality for damage control, film camera tracking, entertainment (e.g., theme parks and games), full body tracking for motion capture, and weapon tracking.

Alternative embodiments can also use other approaches to inertial tracking. For example, rather than performing attitude integration using a direction cosine matrix, attitude integration using Euler angles or quaternions can equivalently be used. Note that the linearized error propagation system matrix and driving noise covariance may depend somewhat on the particular tracking algorithm used. Also, the state of the Kalman filter can be changed, for instance, to include other terms. One example of this is to not only track accelerometer additive bias, as in the embodiments described above, but also to track multiplicative bias (e.g., error in scale factor) of the accelerometer signal, misalignment, and the speed of sound.

Other methods of range measurement can also be used, including acoustic phase, RF or optical time of flight, RF or optical phase, and mechanical cable extension.

Other methods of fusing inertial and acoustic measurements can be used instead of Kalman filtering. For example, neural network, rule-based reasoning, or fuzzy logic systems, or optimization methods, can be used to combine the measurements.

In the description above, only eight different ultrasonic beacon addresses are used. Alternatively, each beacon can be individually addressable, or a larger number of shared addresses can be used. If the beacons are

individually addressable, initial acquisition can be performed, for example, by having beacons also respond to "group" addresses, or to sequence commands addressed to individual beacons during the acquisition phase in such a way that tracking device can "zero in" to ~~it's~~ its initial location by, first finding one beacon that is in range, and then ~~search~~ searching for additional beacons that are closer and closer based on the beacon map known to the tracking device. Such an approach can also be used when the tracking area is made up of several different rooms. Initially, the room that the tracking device ~~is determined~~ is in is determined and then the location within the room can be found.

It is to be understood that the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

Sub a1

1. A method for tracking a motion of a body comprising:

obtaining two types of measurements associated with the motion of the body, one of the types comprising acoustic measurement;

updating an estimate of either an orientation or a position of the body based on one of the two types of measurement; and

updating the estimate based on the other of the two types of measurements.

2. The method of claim 1 in which one of the types of measurement comprises acoustic ranging.

3. The method of claim 1 in which the other of the types of measurement comprises inertial measurement.

Sub a2

4. The method of claim 1 in which the estimate is of orientation.

5. An apparatus for tracking motion of a body comprising:

two sensor systems configured respectively to obtain two types of measurements associated with motion of the body, one of the types comprising acoustic measurement; and

a processor coupled to the two sensor systems and configured to update an estimate of wither an orientation or a position of the body based on one of the two types of measurement, and to update the estimate based on the other

of the two types of measurement.

5, ~~6~~. A tracking device comprising:

a sensor system including

an inertial sensor; and

a set of one or more acoustic sensors rigidly coupled to the inertial sensor; and

a processor programmed to perform the functions of

accepting inertial measurements from the inertial sensor;

updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements;

selecting one of a plurality of acoustic reference devices;

accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device;

updating the location estimate and the orientation estimate using the accepted range measurement.

6, ~~7~~. The tracking device of claim 5, ~~6~~ wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device.

7. ~~8~~. The tracking device of claim 5, ~~6~~ wherein the set

of one or more acoustic sensors includes two or more acoustic sensors.

Sub C3

9. The tracking device of claim 6 wherein updating a location estimate and an orientation estimate using the accepted inertial measurements includes updating an uncertainty in the location and the orientation estimates; and

updating the location estimate and the orientation estimate using the accepted range measurement includes determining an uncertainty in the range measurement, and updating the uncertainty in the location and the orientation estimates using the uncertainty in the range measurement.

10. A method for tracking the motion of a body including:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving an range measurement signal from the reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

10. ~~11~~. The method of claim 9, ~~10~~ further comprising:

determining a range measurement based on a time of flight of the range measurement signal.

12. The method of claim 10 wherein transmitting the control signal includes transmitting a wireless control signal.

Sub A47

13. Software stored on a computer readable medium comprising instructions for causing a computer to perform the functions of:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving an range measurement signal from the reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

14. A tracking system comprising:

an acoustic reference system including a plurality of acoustic reference devices; and

a tracking device including

a sensor system including an inertial sensor and a set of one or more acoustic sensors rigidly coupled to the inertial sensor, and

a processor programmed to perform the functions of accepting inertial measurements from the inertial sensor, updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements,

selecting one of a plurality of acoustic reference devices, accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device, and updating the location estimate and the orientation estimate using the accepted range measurement.

15. The system of claim 14 wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device, and wherein each acoustic reference device includes a receiver for receiving the control signal from the sensor system, and an acoustic transducer for sending the acoustic signal.

09-062442

MOTION TRACKING SYSTEM

Abstract

Tracking a motion of a body by obtaining two types of measurements associated with the motion of the body, one of the types including acoustic measurement. An estimate of either an orientation or a position of the body is updated based on one of the two types of measurement, for example based on inertial measurement. The estimate is then updated based on the other of the two types of measurements, for example based on acoustic ranging. The invention also features determining range measurement to selected reference devices that are fixed in the environment of the body.

302027.B11

PATENT
ATTORNEY DOCKET NO: 09970/002001

COMBINED DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled MOTION TRACKING SYSTEM, the specification of which

■ is attached hereto.
☐ was filed on ______________________ as Application Serial No. ______________________
and was amended on ______________________.
☐ was described and claimed in PCT International Application No. ______________________
filed on ________________ and as amended under PCT Article 19 on ________________.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose all information I know to be material to patentability in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby appoint the following attorneys and/or agents to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: David L. Feigenbaum, Reg. No. 30,378; and J. Robin Rohlicek, Reg. No. P-43,349.

Address all telephone calls to David L. Feigenbaum at telephone number 617/542-5070.

Address all correspondence to David L. Feigenbaum, Fish & Richardson P.C., 225 Franklin Street, Boston, MA 02110-2804.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patents issued thereon.

Full Name of Inventor: Eric M. Foxlin

Inventor's Signature: ______________________ Date: ______________

Residence Address: 285 Highland Avenue, Arlington, MA 02174

Citizen of: U.S.A.

Post Office Address: 285 Highland Avenue, Arlington, MA 02174

302003.B11

400
383

3736
1-16

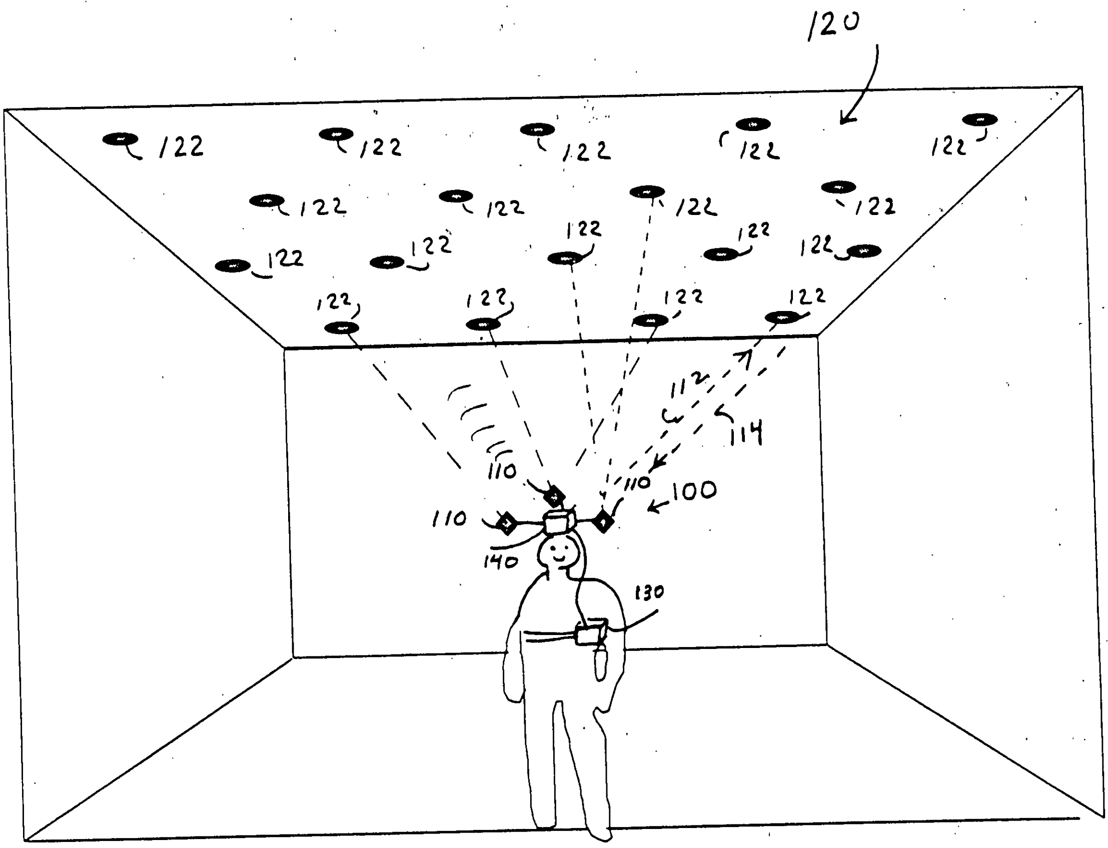


Fig. 1

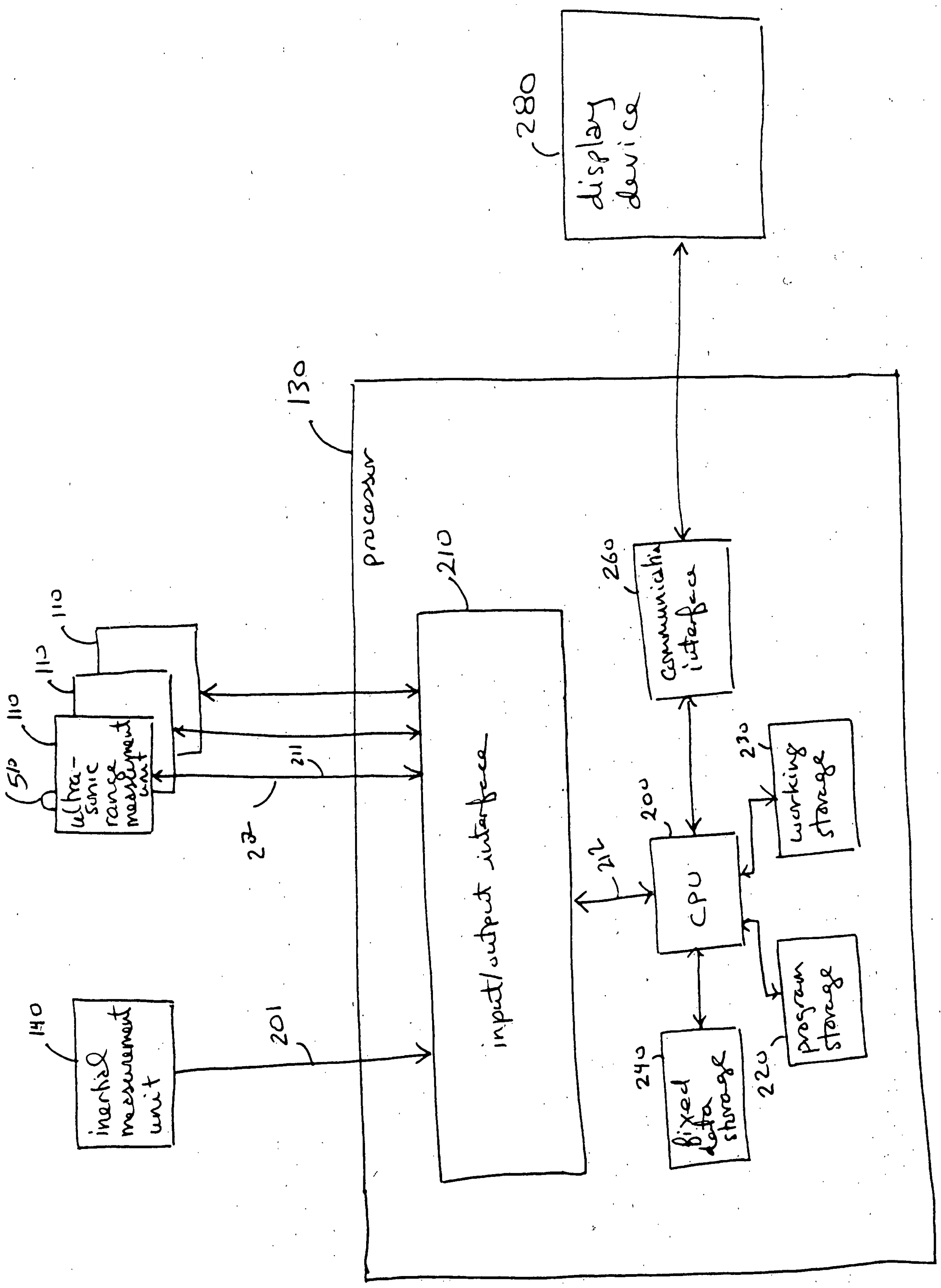

280
display device
130
processor
210
input/output interface
260
communication interface
200
CPU
212
230
working storage
220
program storage
240
fixed data storage
110
110
110
510
ultra-sonic range measurement unit
211
201
140
inertial measurement unit

Fig. 2

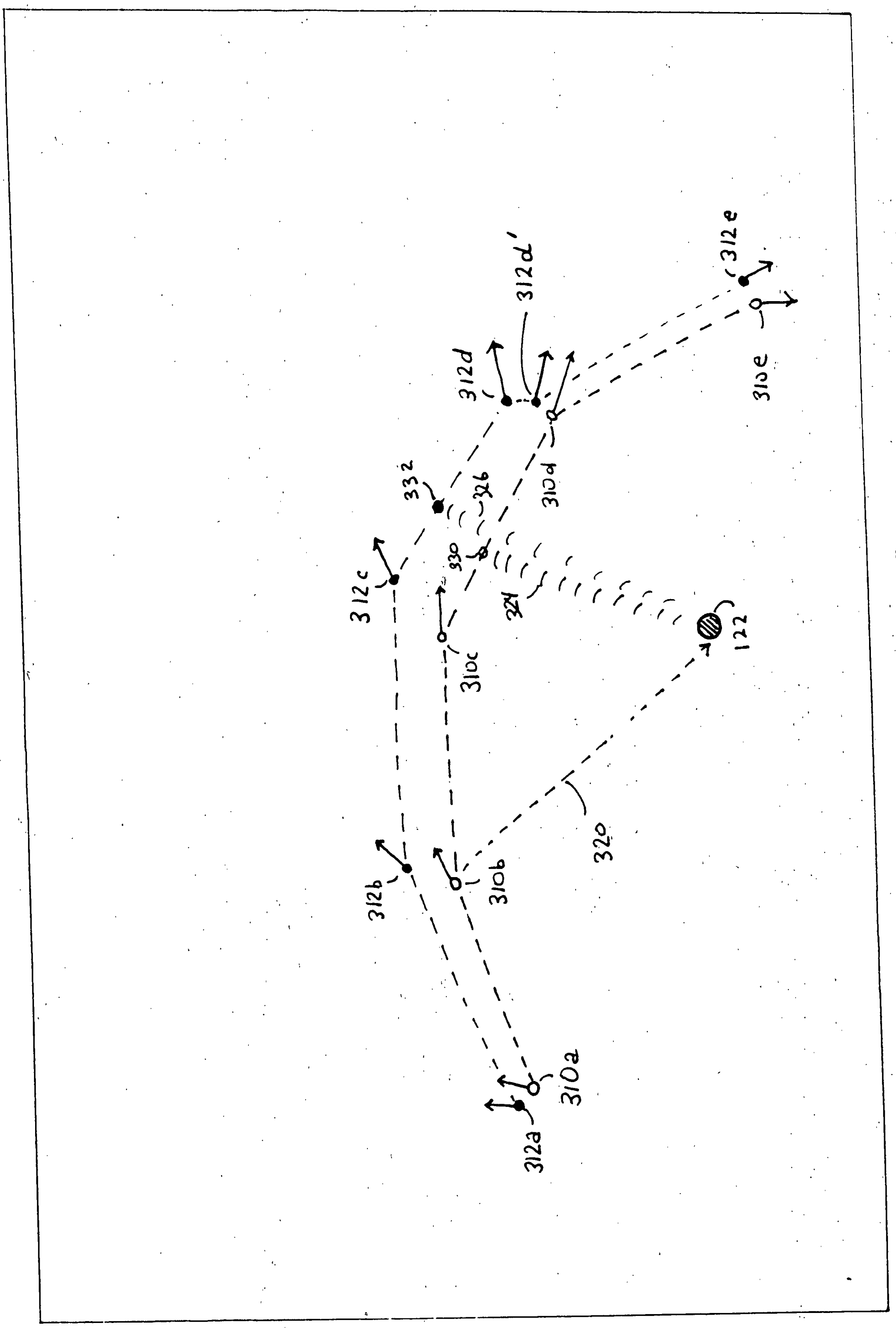

312a
310a
312b
310b
320
312c
310c
332
326
330
324
122
312d
312d'
310d
312e
310e

Fig 3

140

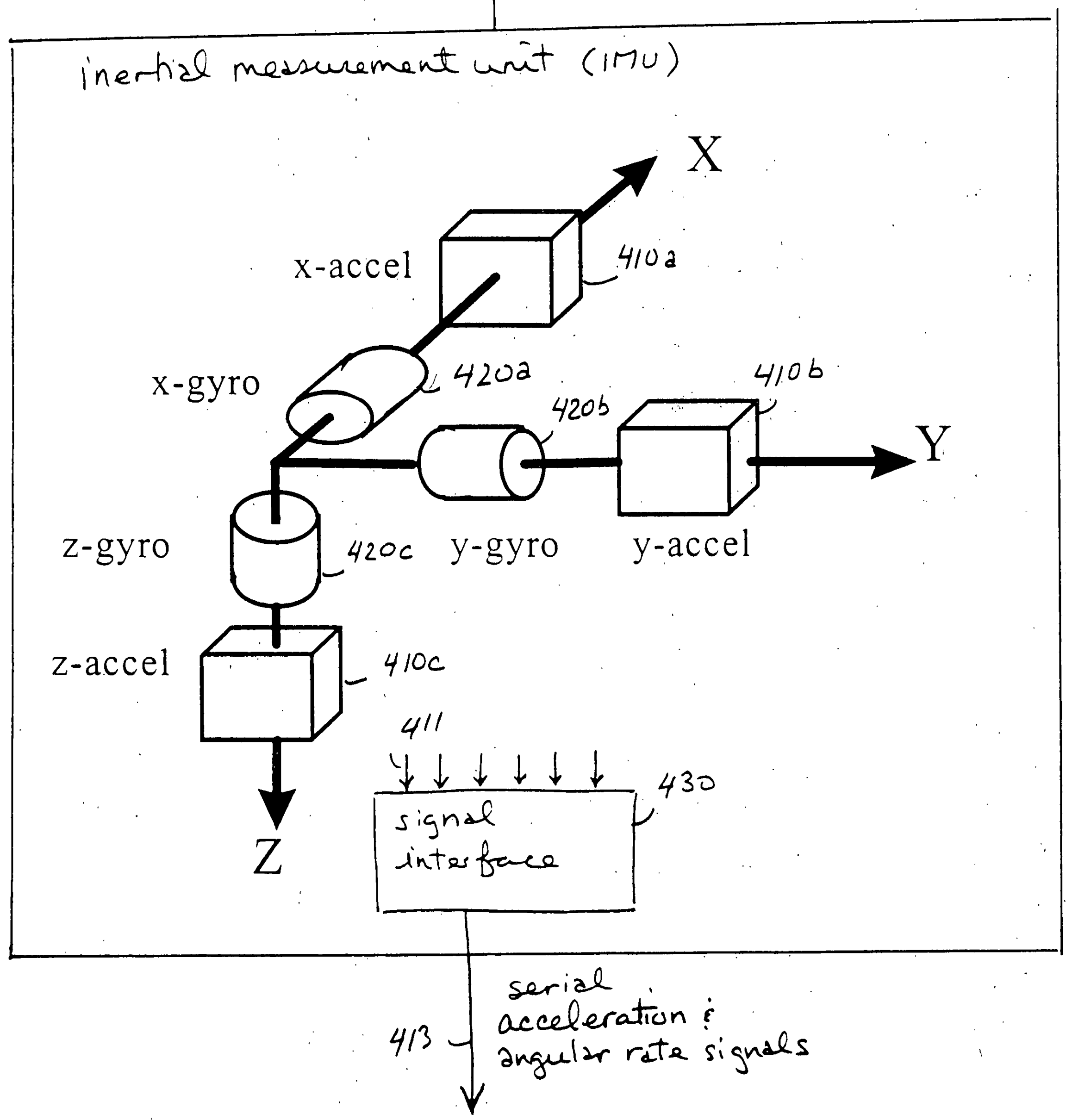

inertial measurement unit (IMU)
X
x-accel
410a
x-gyro
420a
410b
420b
Y
z-gyro
420c
y-gyro
y-accel
z-accel
410c
411
430
signal
interface
Z
serial
acceleration &
angular rate signals
413

Fig. 4

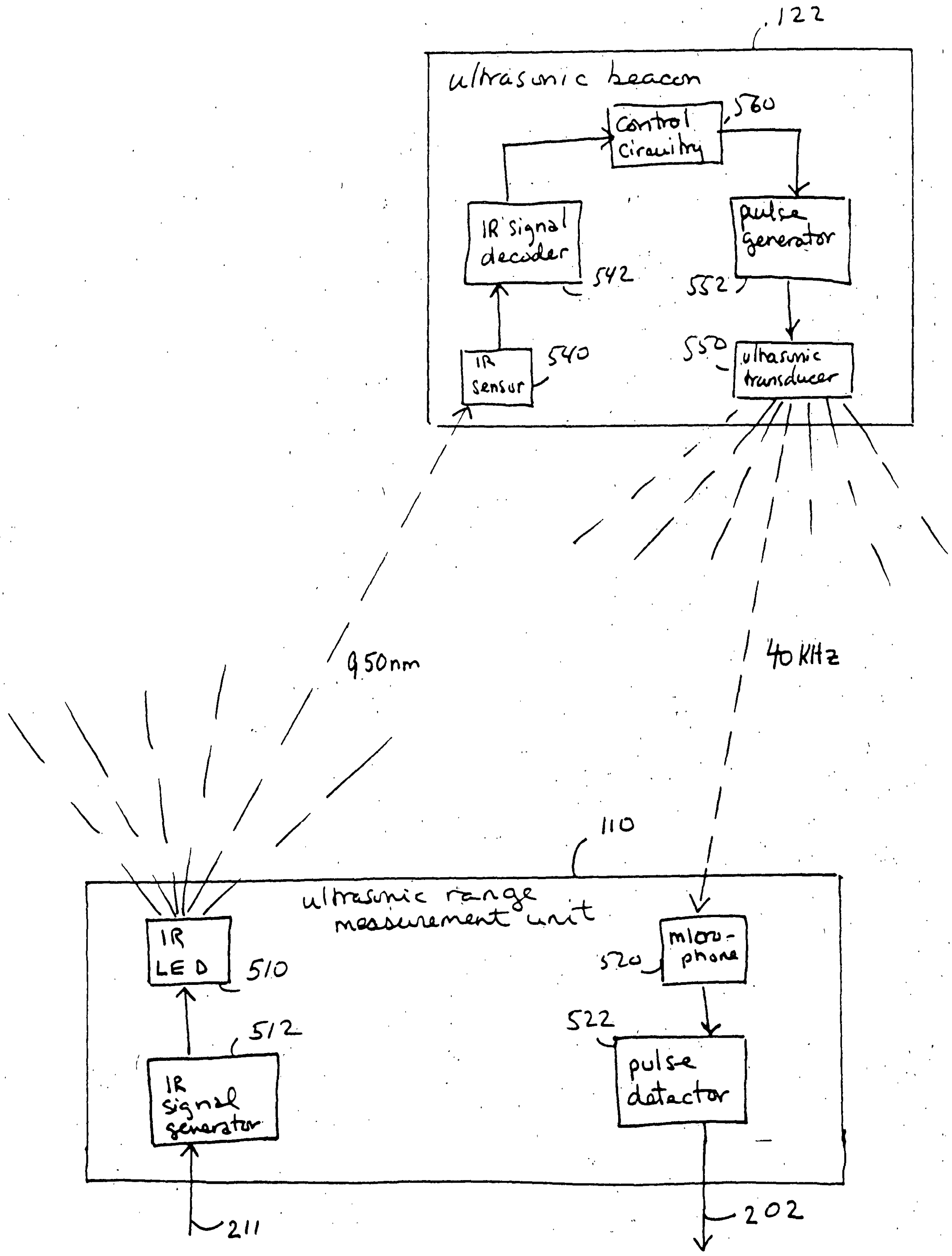

122
ultrasonic beacon
control circuitry
560
IR signal decoder
542
pulse generator
552
IR sensor
540
550
ultrasonic transducer
950nm
40 KHz
110
ultrasonic range measurement unit
IR LED
510
micro-phone
520
512
522
IR signal generator
pulse detector
211
202

Fig. 5

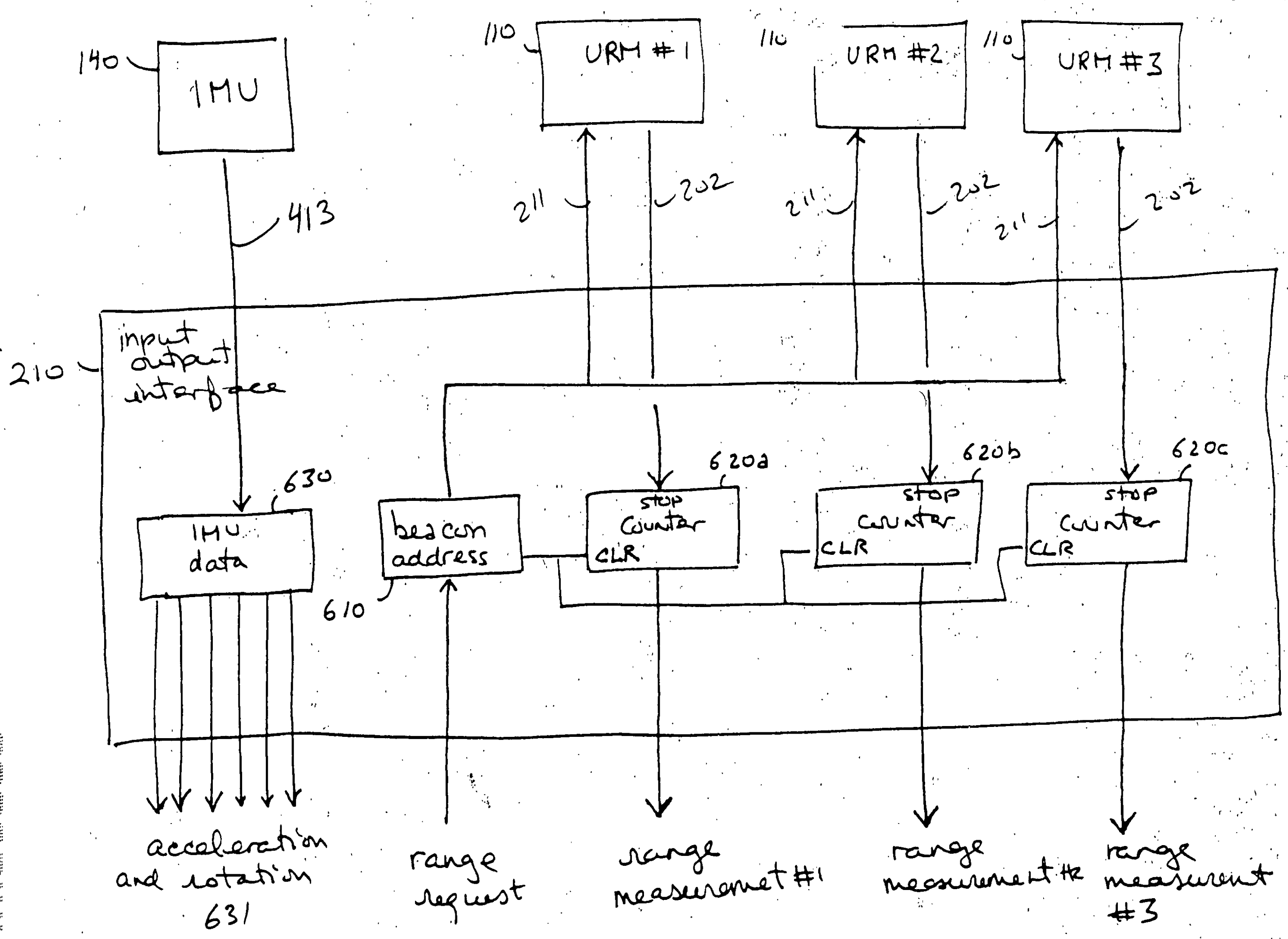

140
IMU
413
110
URM #1
URM #2
URM #3
211
202
210
input output interface
630
IMU data
beacon address
610
stop counter
CLR
620a
620b
620c
acceleration and rotation
631
range request
range measurement #1
range measurement
range measurent #3

Fig. 6

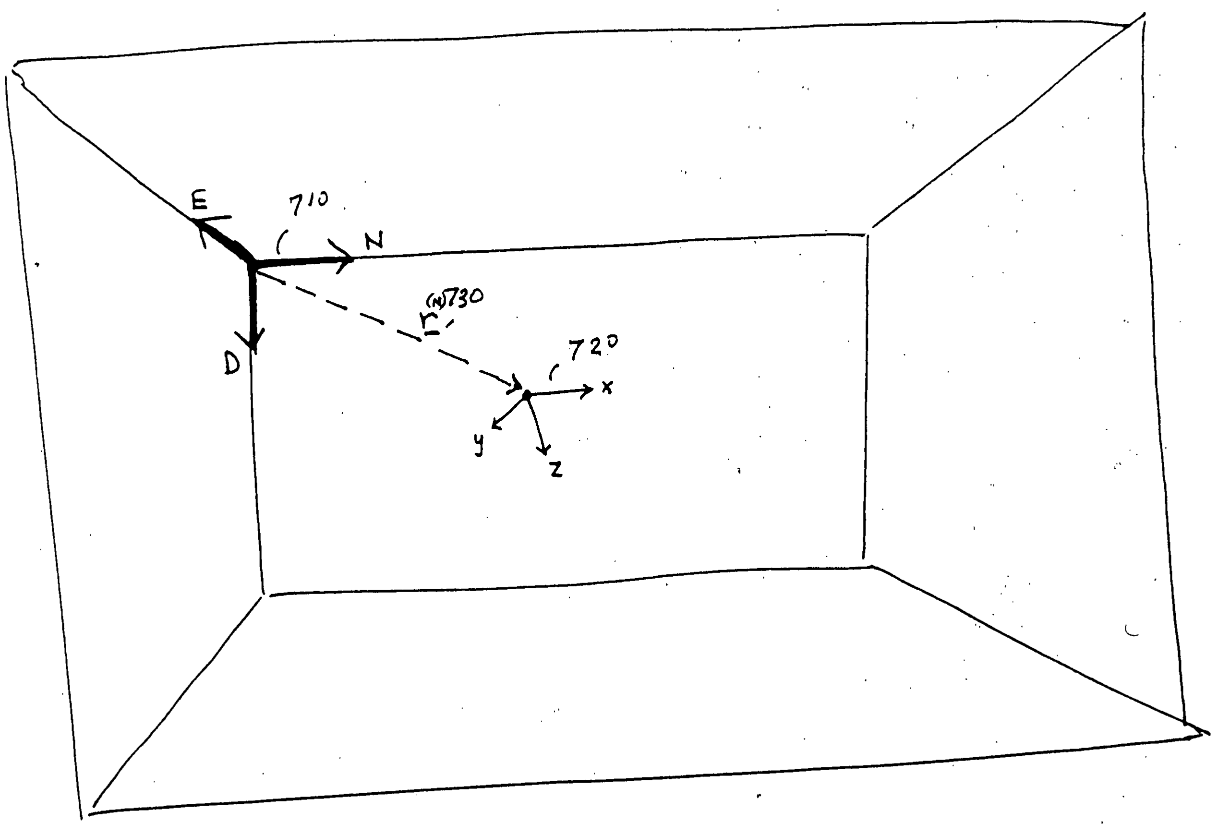

E
710
N
D
730
720
x
y
z

Fig. 7a

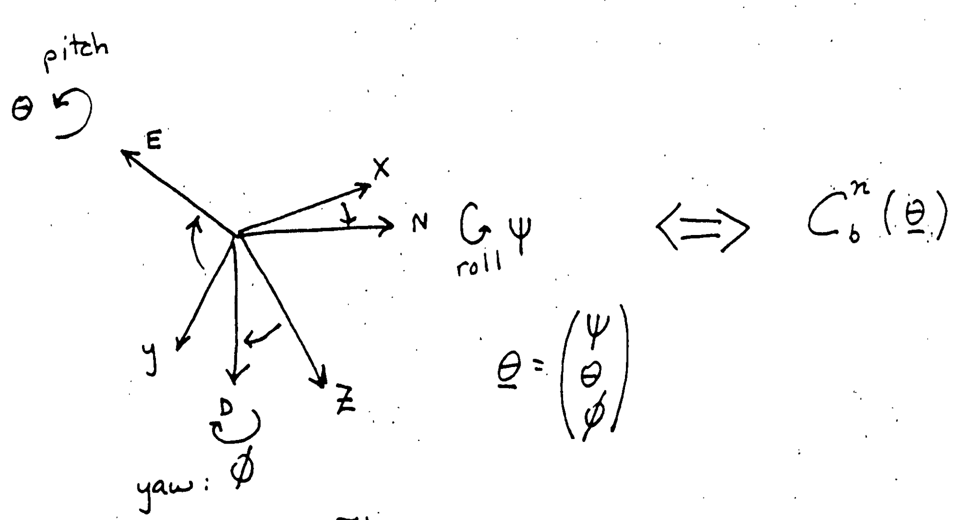

pitch
θ
E
X
N
roll
ψ
y
D
Z
yaw : φ
⟺ $C_b^n(\underline{\theta})$
$\underline{\theta} = \begin{pmatrix} \psi \\ \theta \\ \phi \end{pmatrix}$

Fig. 7b

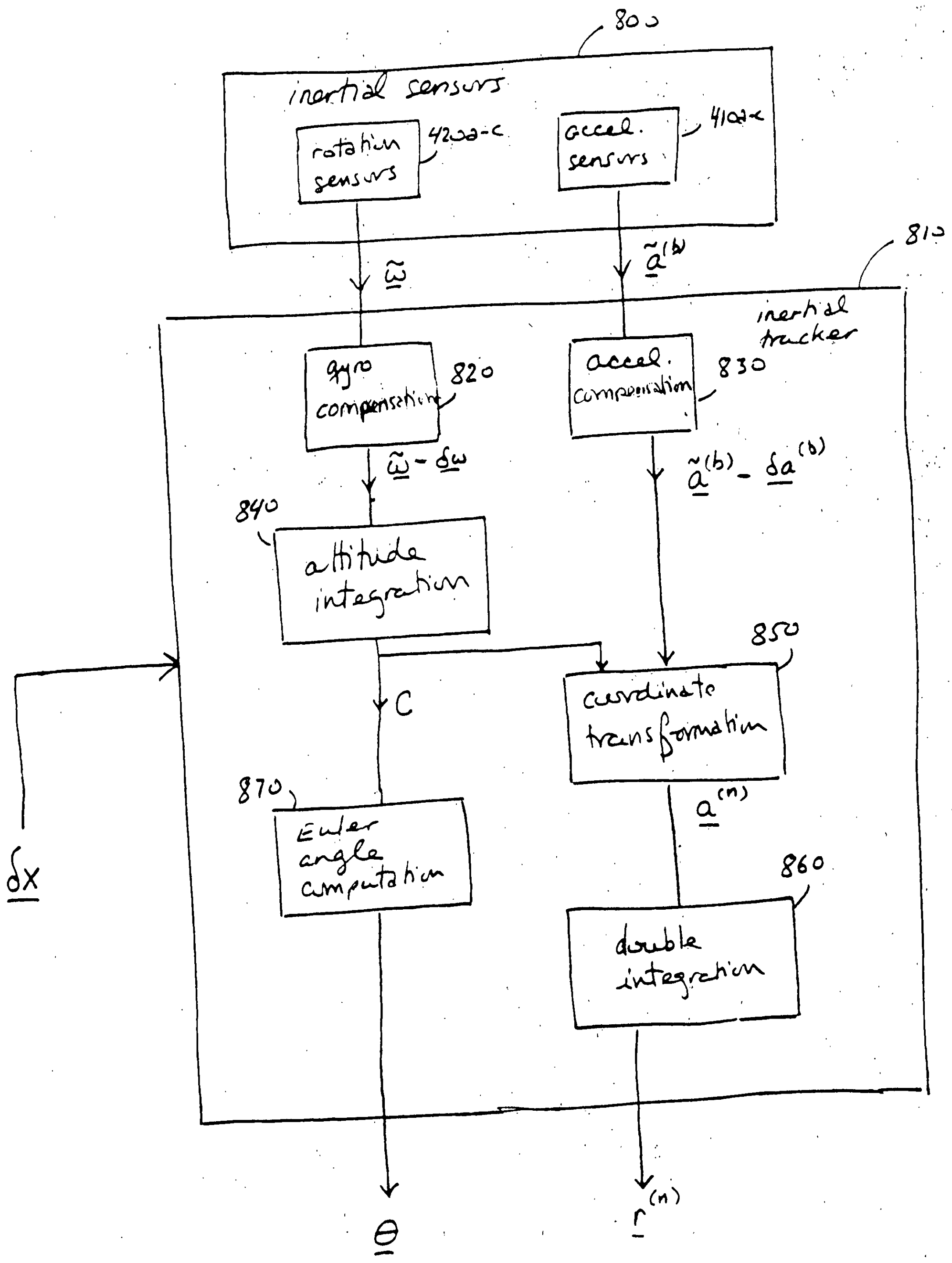

800
inertial sensors
rotation sensors
420a-c
accel. sensors
410a-c
810
$\tilde{\omega}$
$\tilde{a}^{(b)}$
inertial tracker
gyro compensation
820
accel. compensation
830
$\tilde{\omega} - \delta\omega$
$\tilde{a}^{(b)} - \delta a^{(b)}$
840
attitude integration
850
coordinate transformation
C
δx
870
Euler angle computation
$a^{(n)}$
860
double integration
θ
$r^{(n)}$

Fig. 8

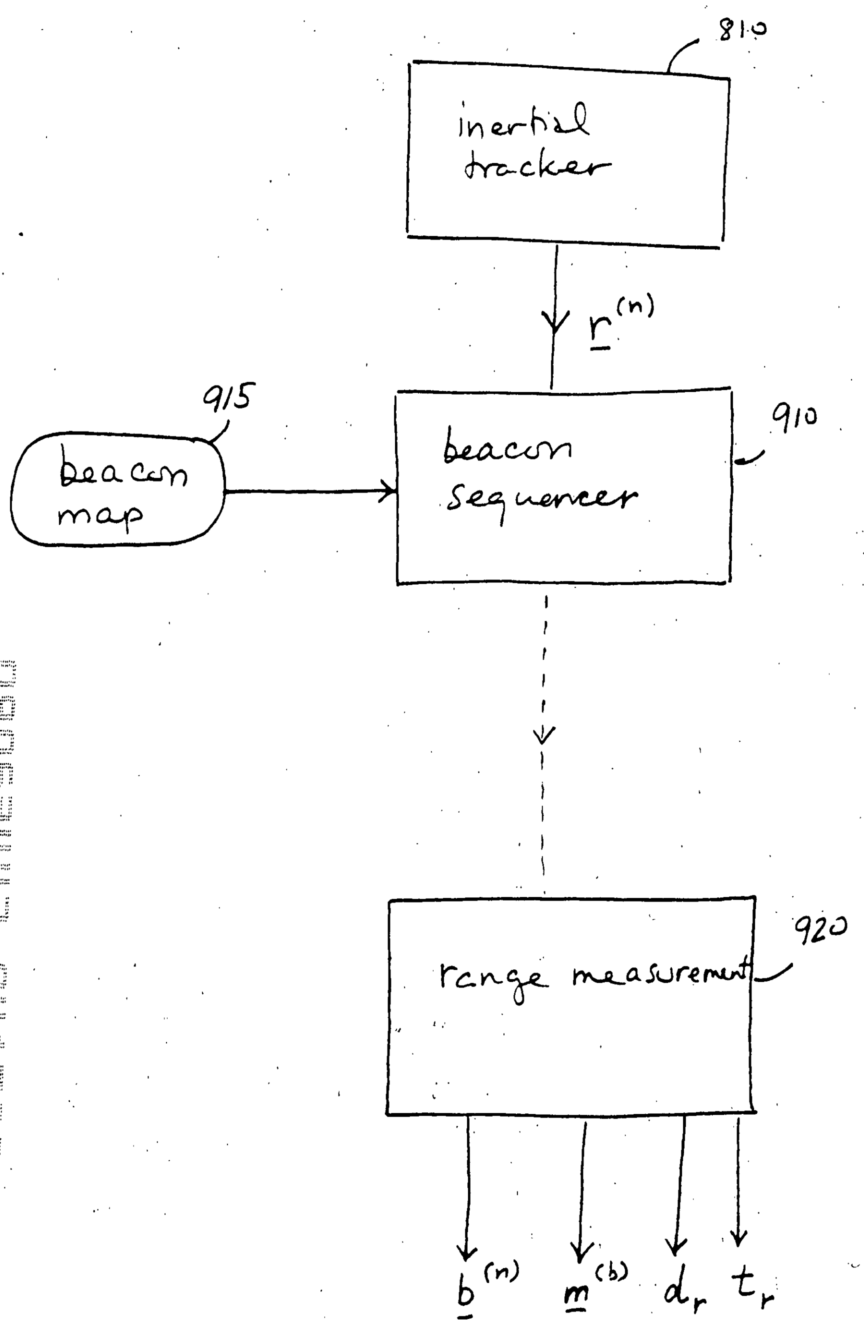

810
inertial
tracker
$\underline{r}^{(n)}$
915
beacon
map
910
beacon
sequencer
920
range measurement
$\underline{b}^{(n)}$
$\underline{m}^{(b)}$
d_r
t_r

Fig. 9

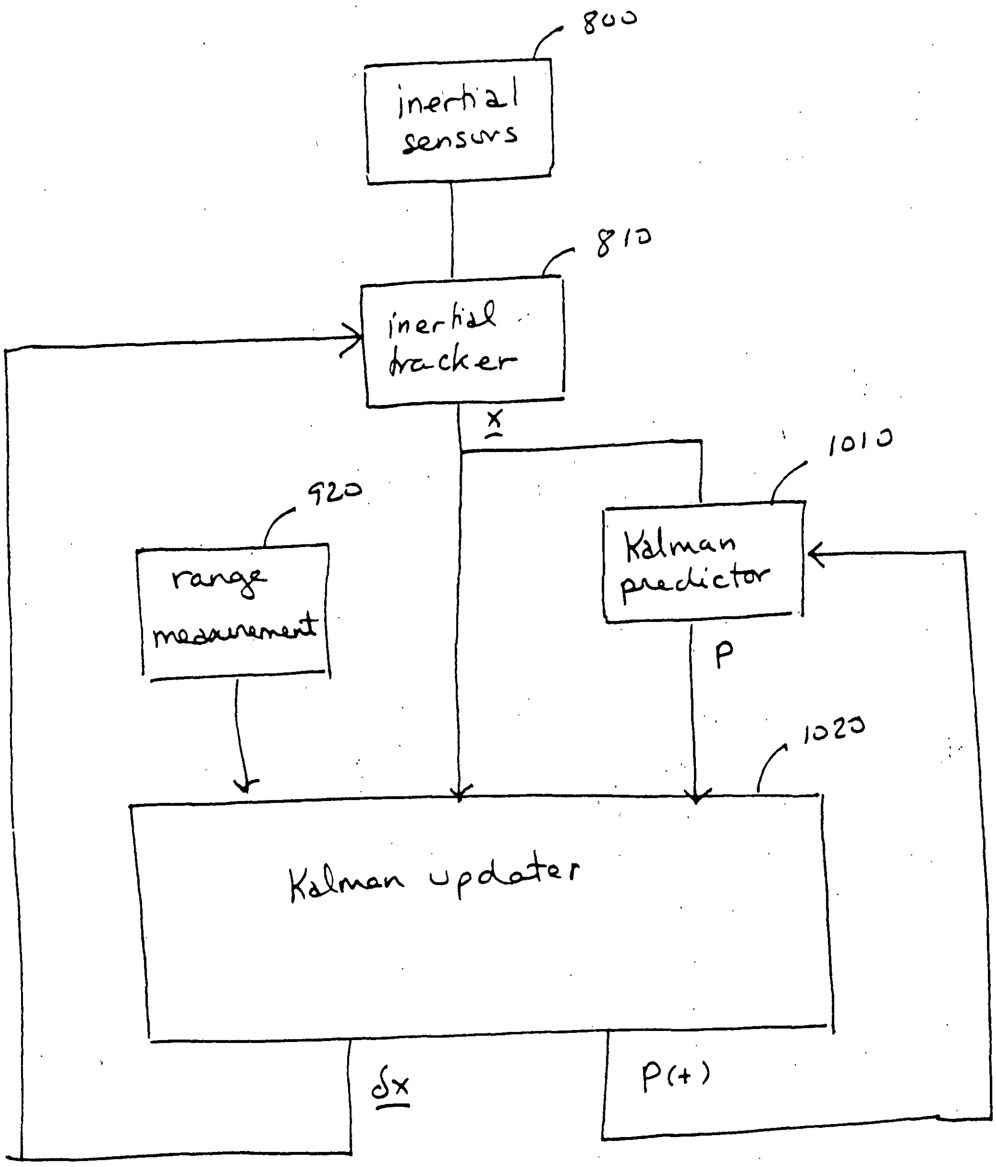

800
inertial sensors
810
inertial tracker
x
1010
920
range measurement
Kalman predictor
P
1020
Kalman updater
δx
P(+)

Fig. 10

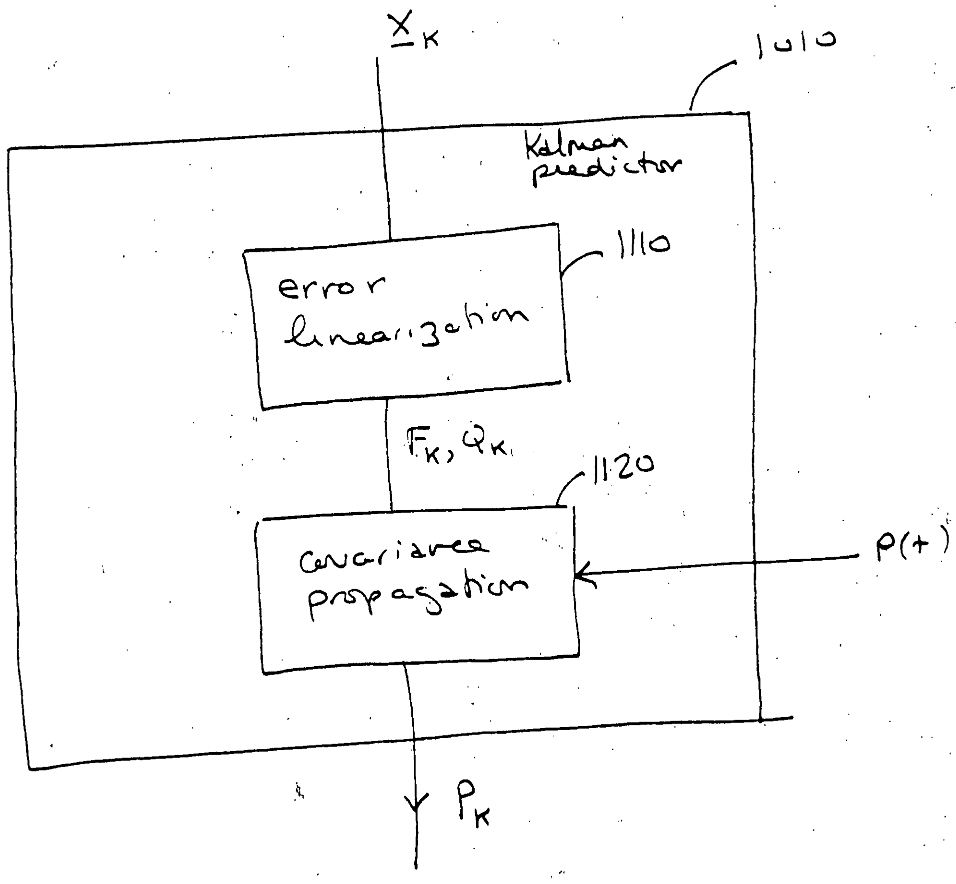

$\underline{X}_K$
1010
Kalman predictor
1110
error linearization
F_K, Q_K
1120
covariance propagation
$P(+)$
P_K

Fig. 11

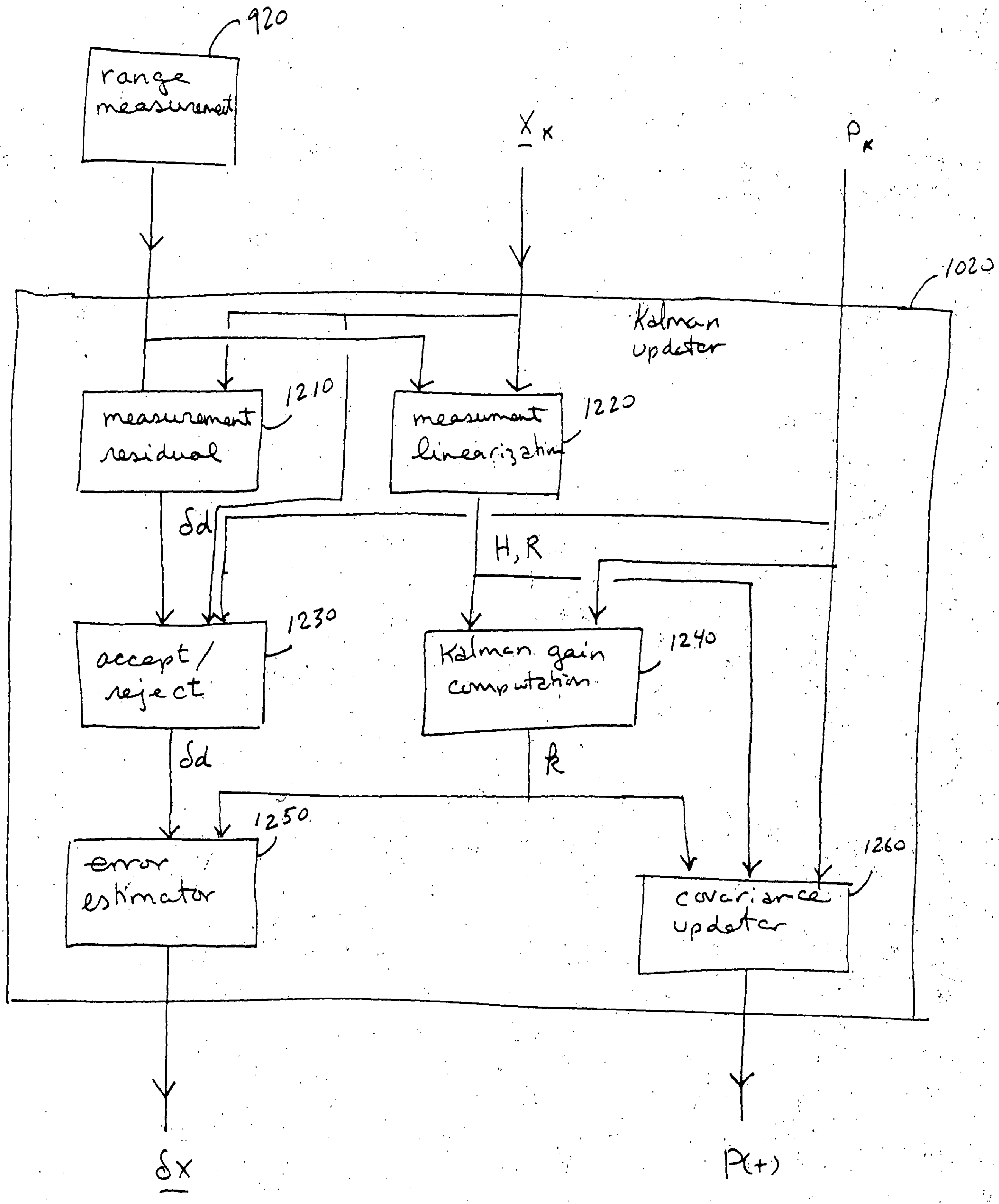
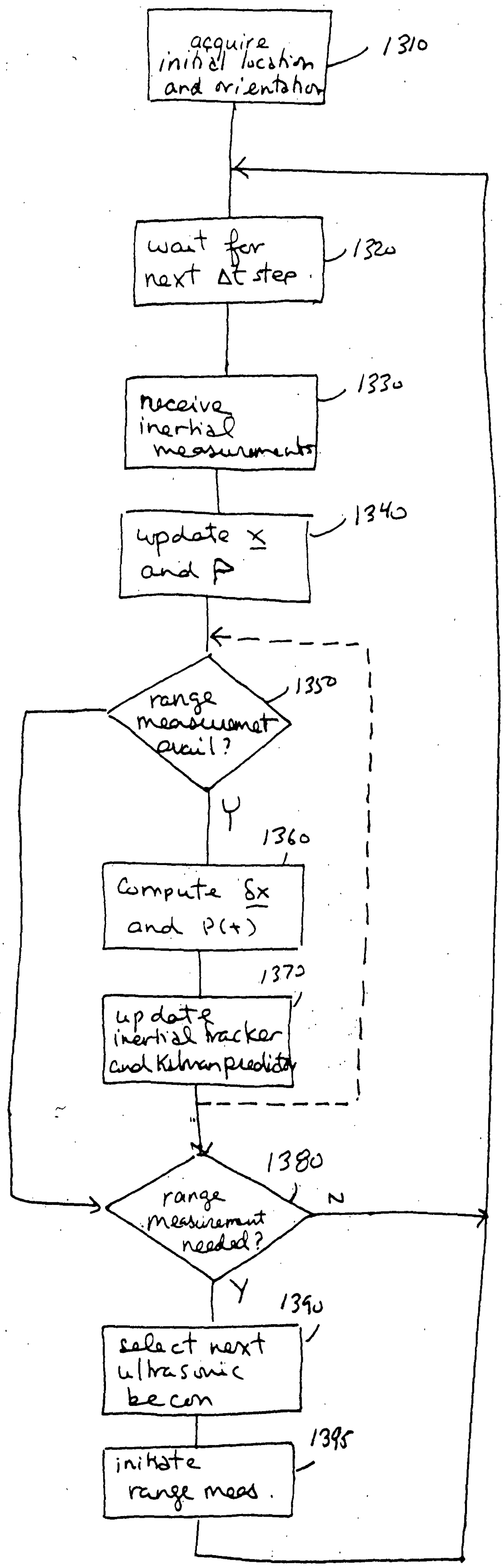

920
range measurement
$\underline{X}_K$
P_K
1020
Kalman updater
measurement residual
1210
measurement linearization
1220
δd
H, R
accept / reject
1230
Kalman gain computation
1240
δd
K
1250
error estimator
1260
covariance updater
$\underline{\delta x}$
P(+)

Fig. 12



acquire initial location and orientation
1310
wait for next Δt step
1320
receive inertial measurements
1330
update x and P
1340
range measurement avail?
1350
Y
1360
Compute δx and P(+)
1370
update inertial tracker and Kalman predictor
1380
range measurement needed?
N
Y
1390
select next ultrasonic beacon
1395
initiate range meas.

Fig. 13

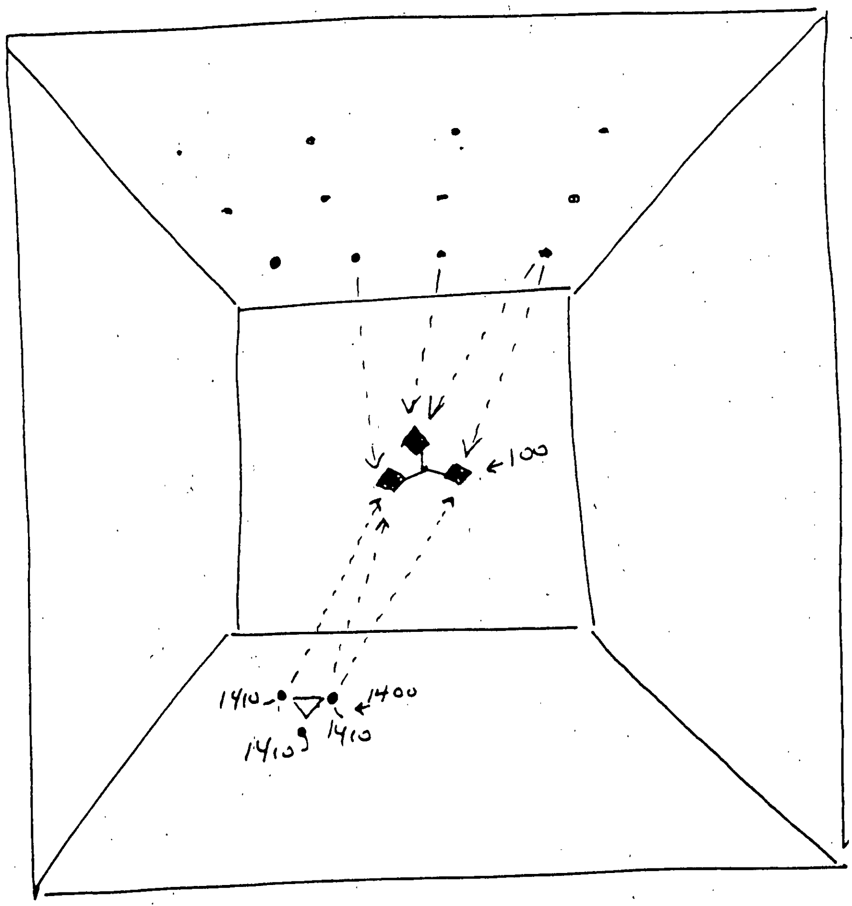


Fig. 14a

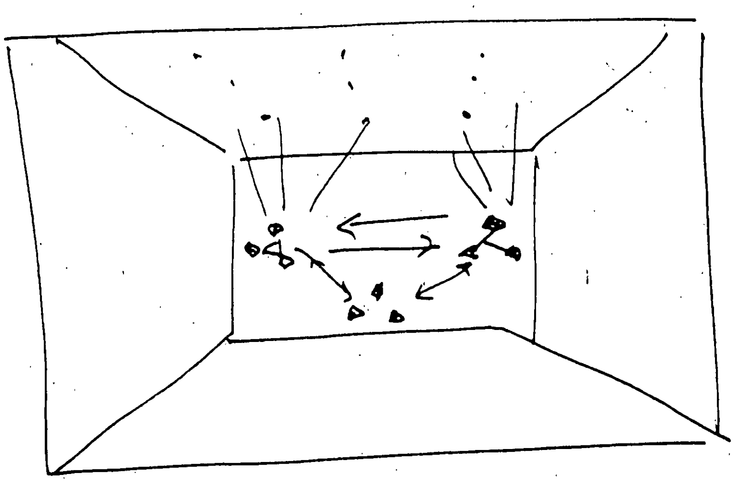


Fig 14b

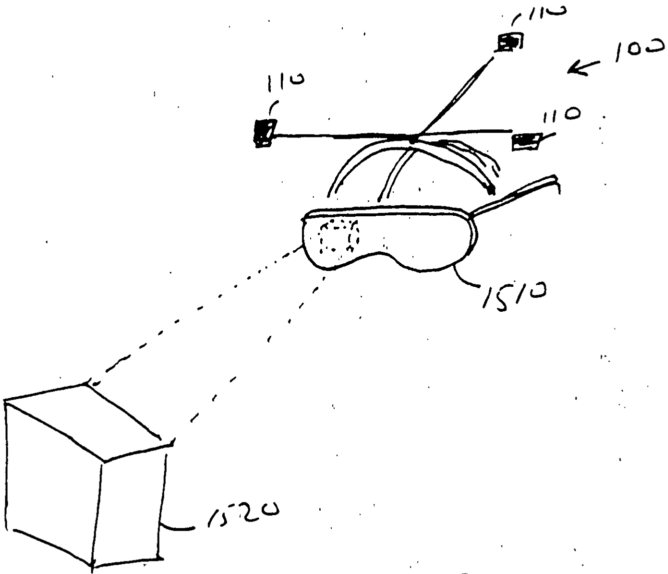


Fig. 15

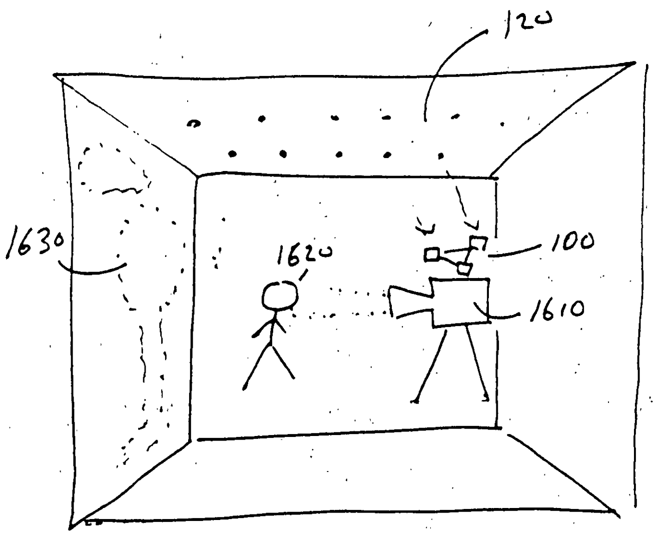


Fig. 16

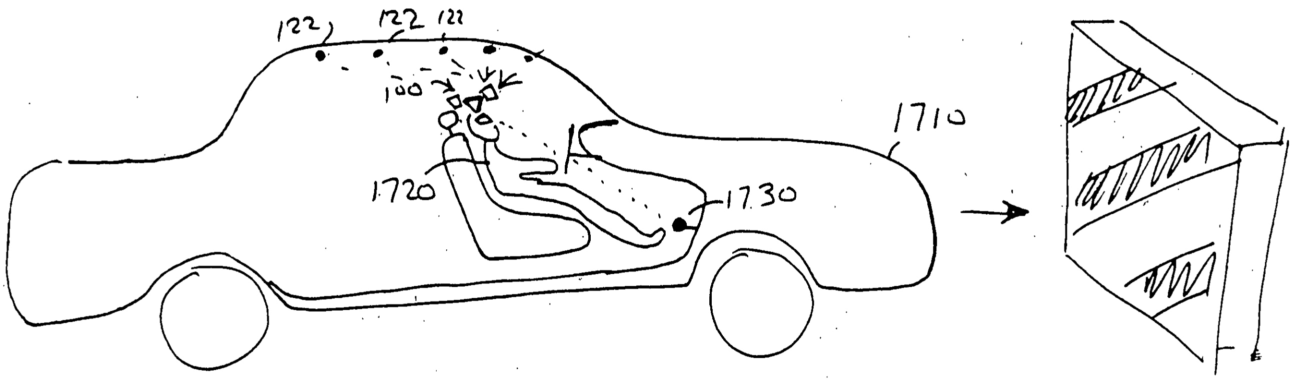


Fig. 17

600
343

3736
1-16

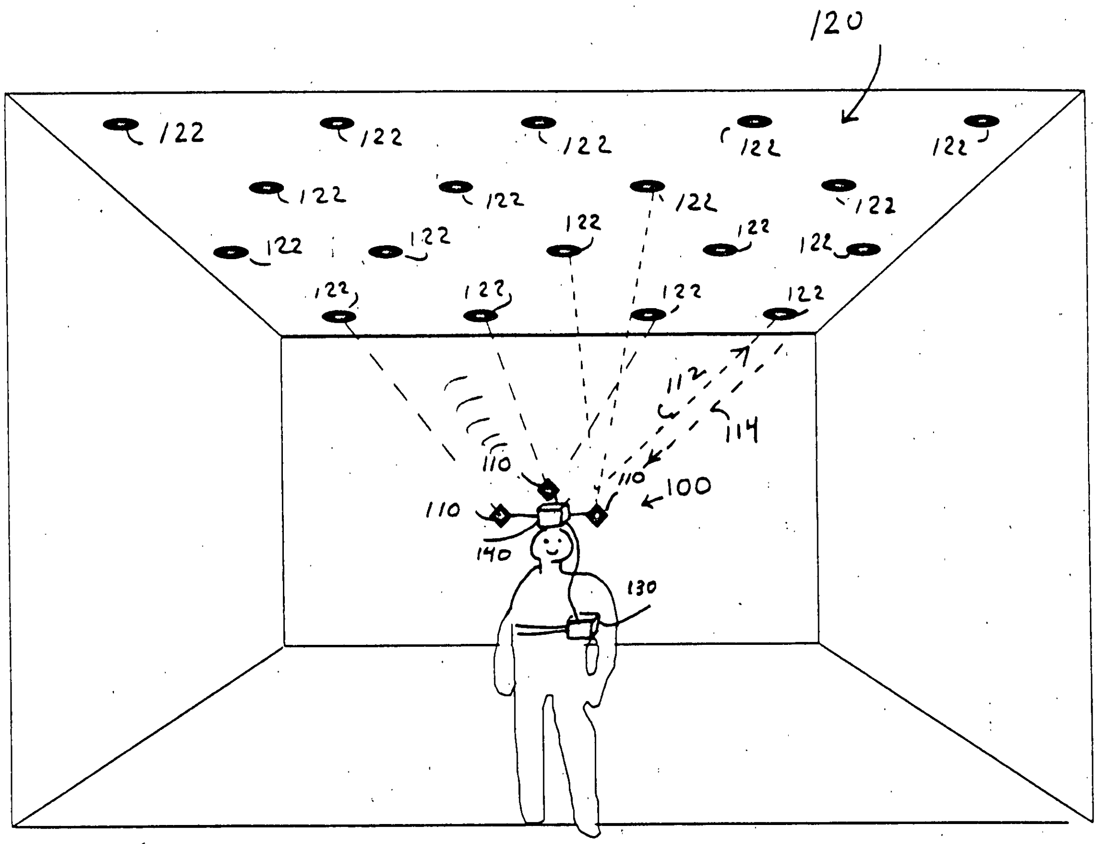


Fig. 1

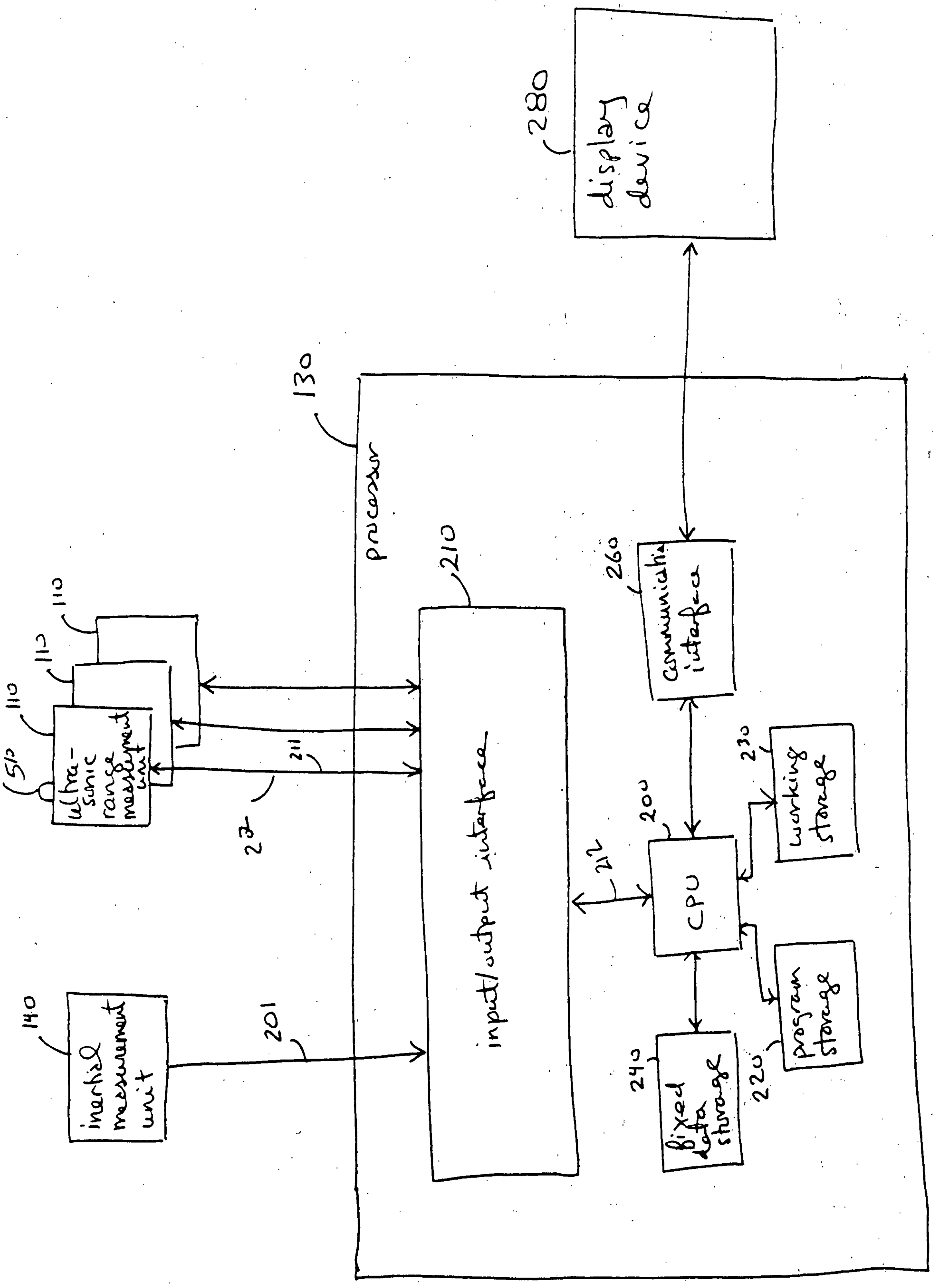

280
display device
130
processor
210
input/output interface
260
communication interface
200
CPU
212
230
working storage
220
program storage
240
fixed data storage
110
110
110
510
ultra-sonic range measurement unit
211
22
140
inertial measurement unit
201

Fig. 2

PRINT OF DRAWINGS
AS ORIGINALLY FILED

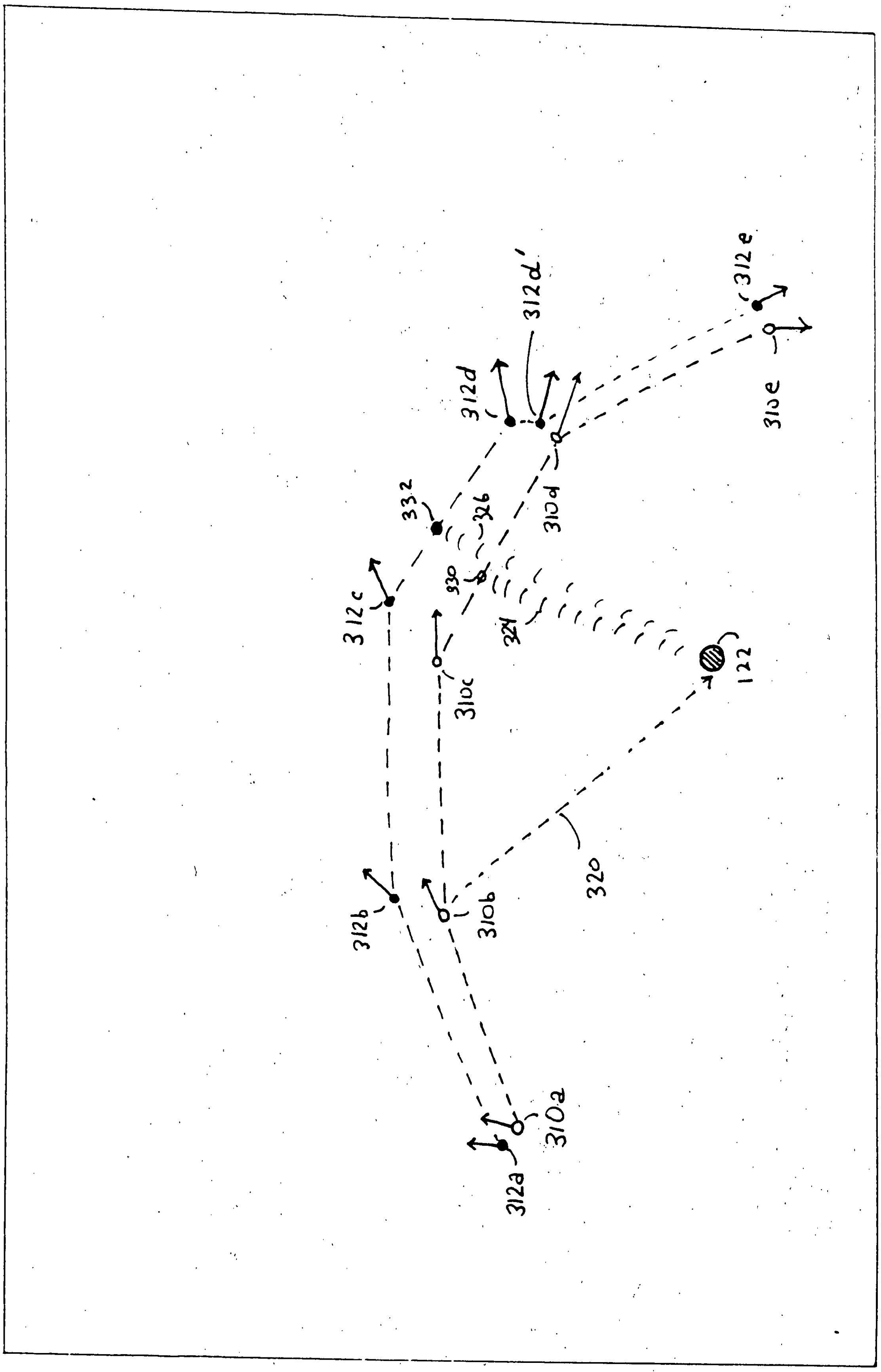


Fig 3

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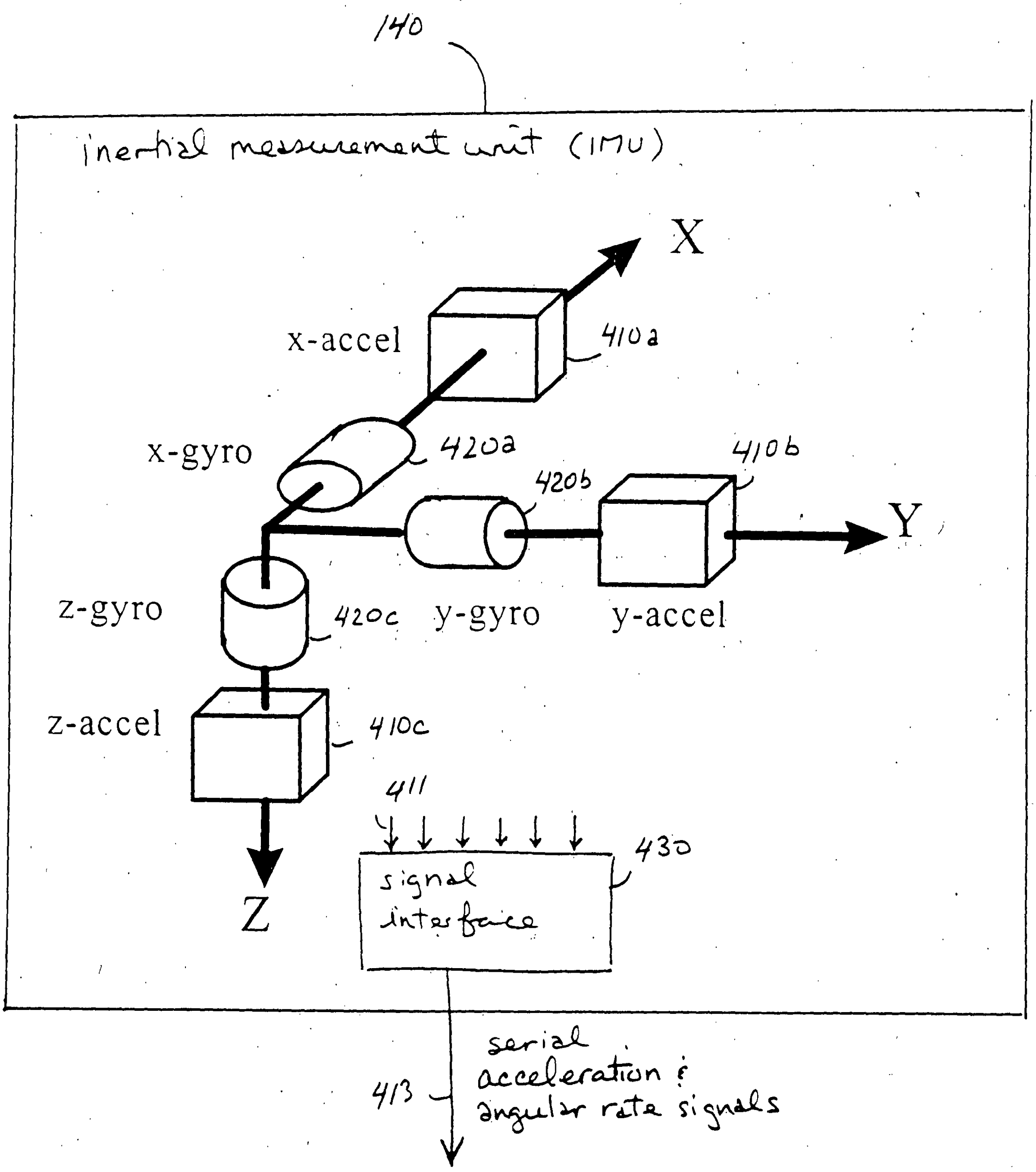
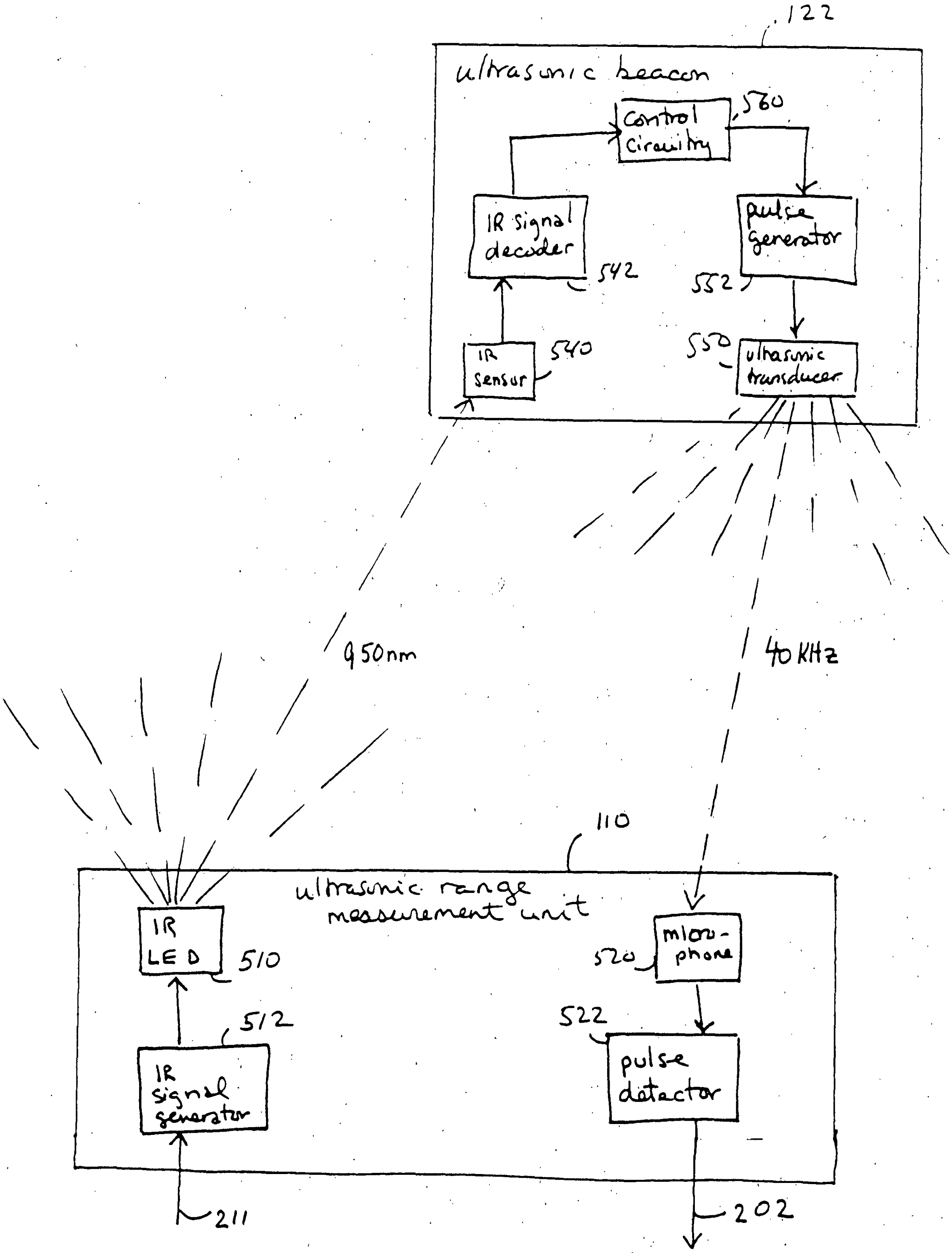


Fig. 4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ultrasonic beacon
control circuitry
560
IR signal decoder
542
pulse generator
552
IR sensor
540
550
ultrasonic transducer
950nm
40 KHz
110
ultrasonic range measurement unit
IR LED
510
512
IR signal generator
micro-phone
520
522
pulse detector
211
202

Fig. 5

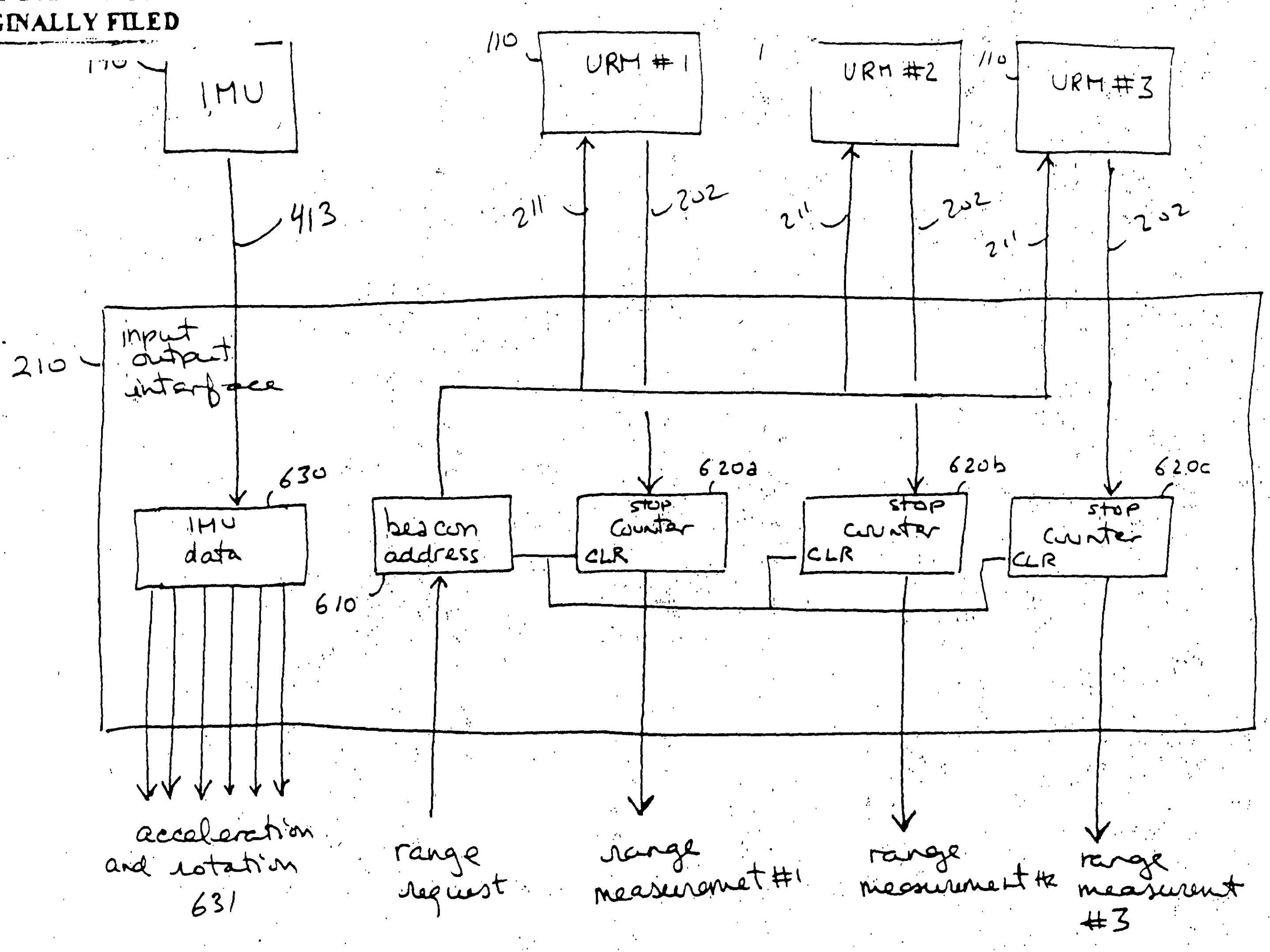
110
IMU
413
110
URM #1
211
202
URM #2
211
202
110
URM #3
211
202
210
input output interface
630
IMU data
beacon address
610
stop counter CLR
620a
stop counter CLR
620b
stop counter CLR
620c
acceleration and rotation 631
range request
range measurement #1
range measurement #2
range measurement #3

Fig. 6

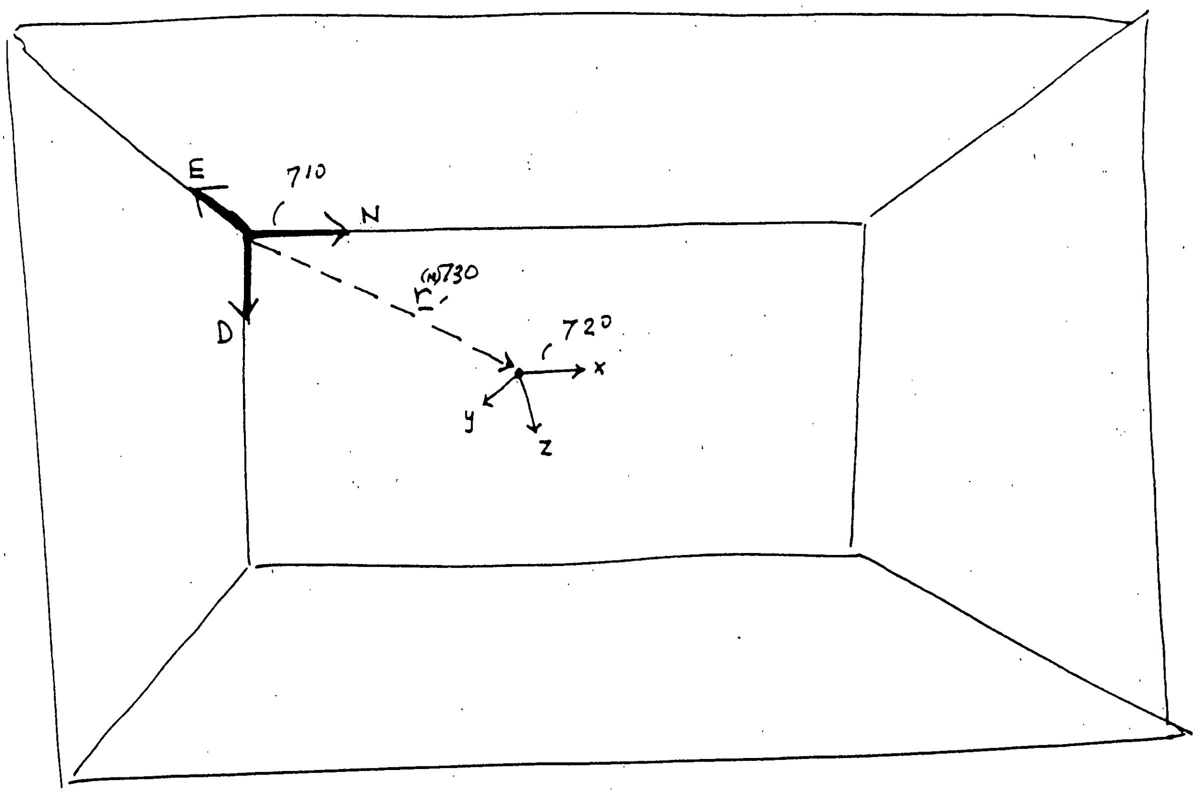
E
710
N
D
730
r
720
x
y
z

Fig. 7a

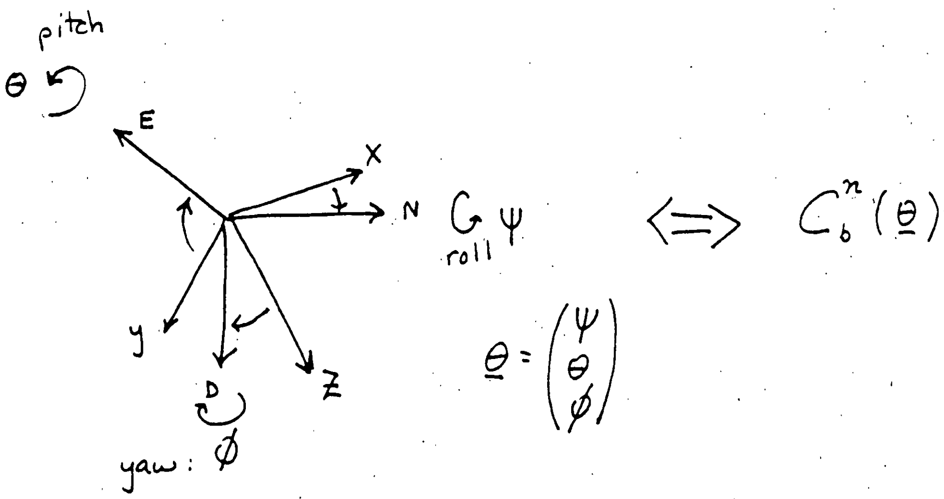
pitch
θ
E
X
N
ψ
roll
y
D
Z
yaw : φ
⟺
$C_b^n(\underline{\theta})$
$\underline{\theta} = \begin{pmatrix} \psi \\ \theta \\ \phi \end{pmatrix}$

Fig. 7b

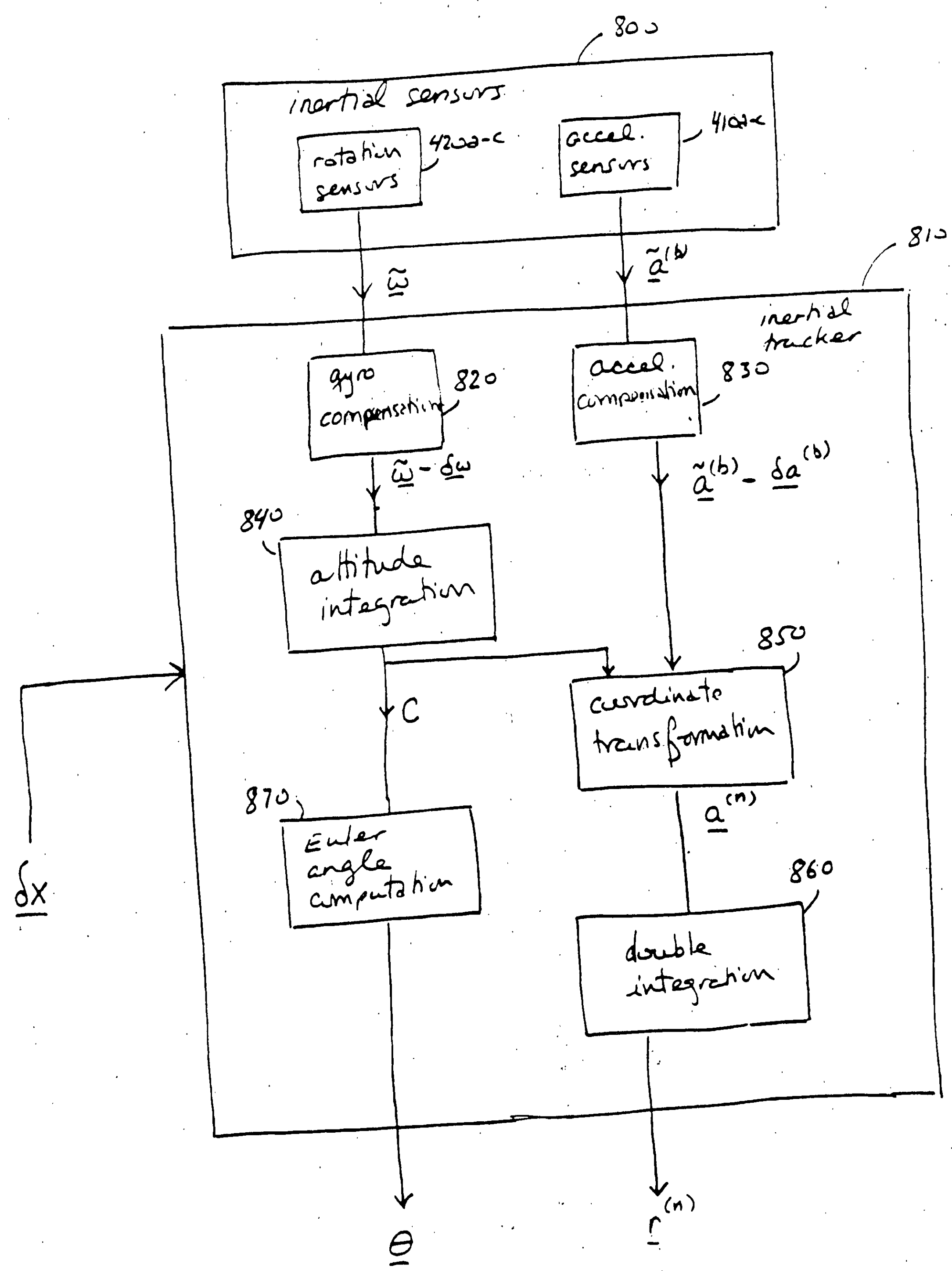
800
inertial sensors
rotation sensors
420a-c
accel. sensors
410a-c
810
$\tilde{\omega}$
$\tilde{a}^{(b)}$
inertial tracker
gyro compensation
820
accel. compensation
830
$\tilde{\omega} - \delta\omega$
$\tilde{a}^{(b)} - \delta a^{(b)}$
840
attitude integration
850
coordinate transformation
C
870
Euler angle computation
$a^{(n)}$
860
double integration
δx
θ
$r^{(n)}$

Fig. 8

RINT OF DRAWINGS
AS ORIGINALLY FILED

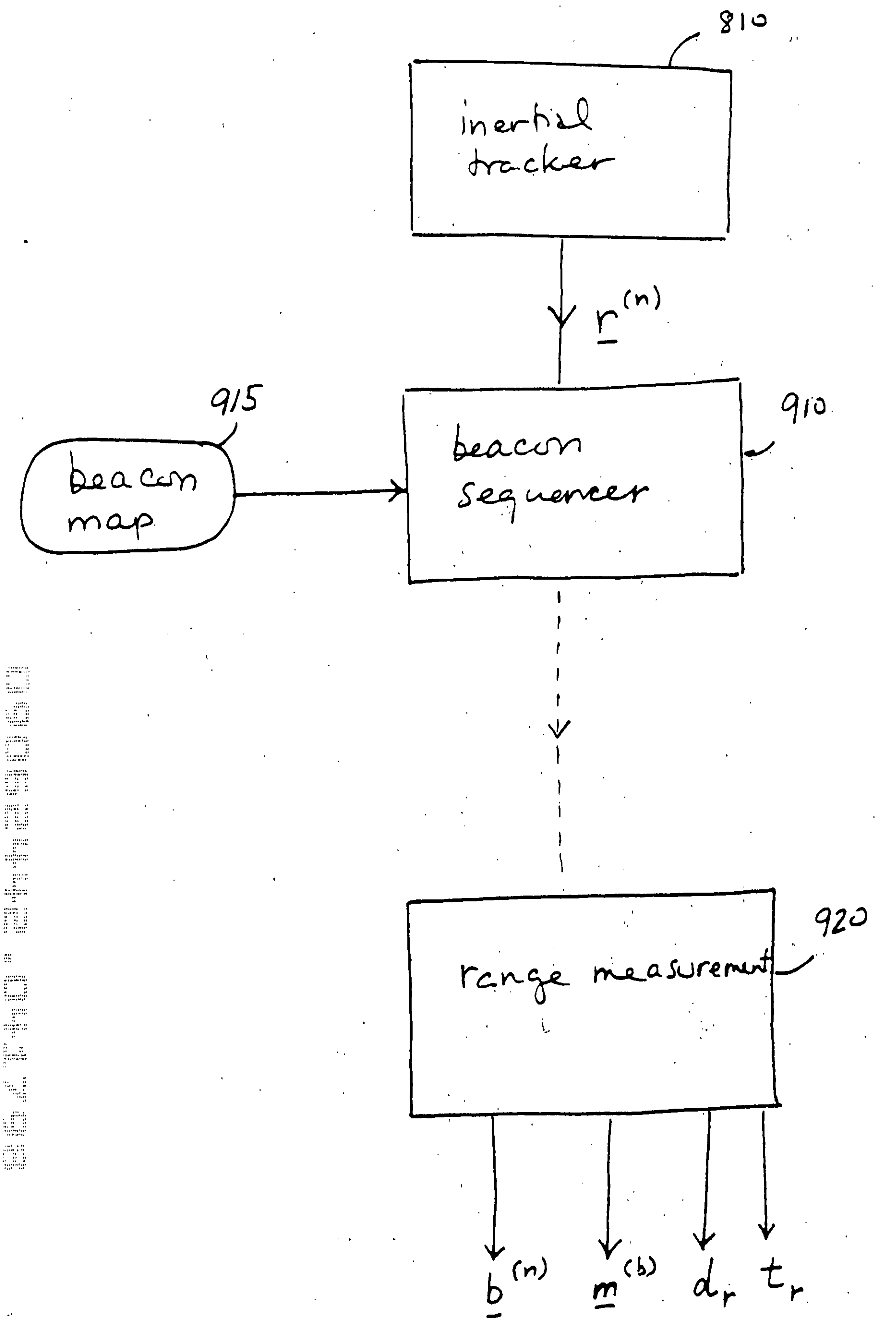

Fig. 9

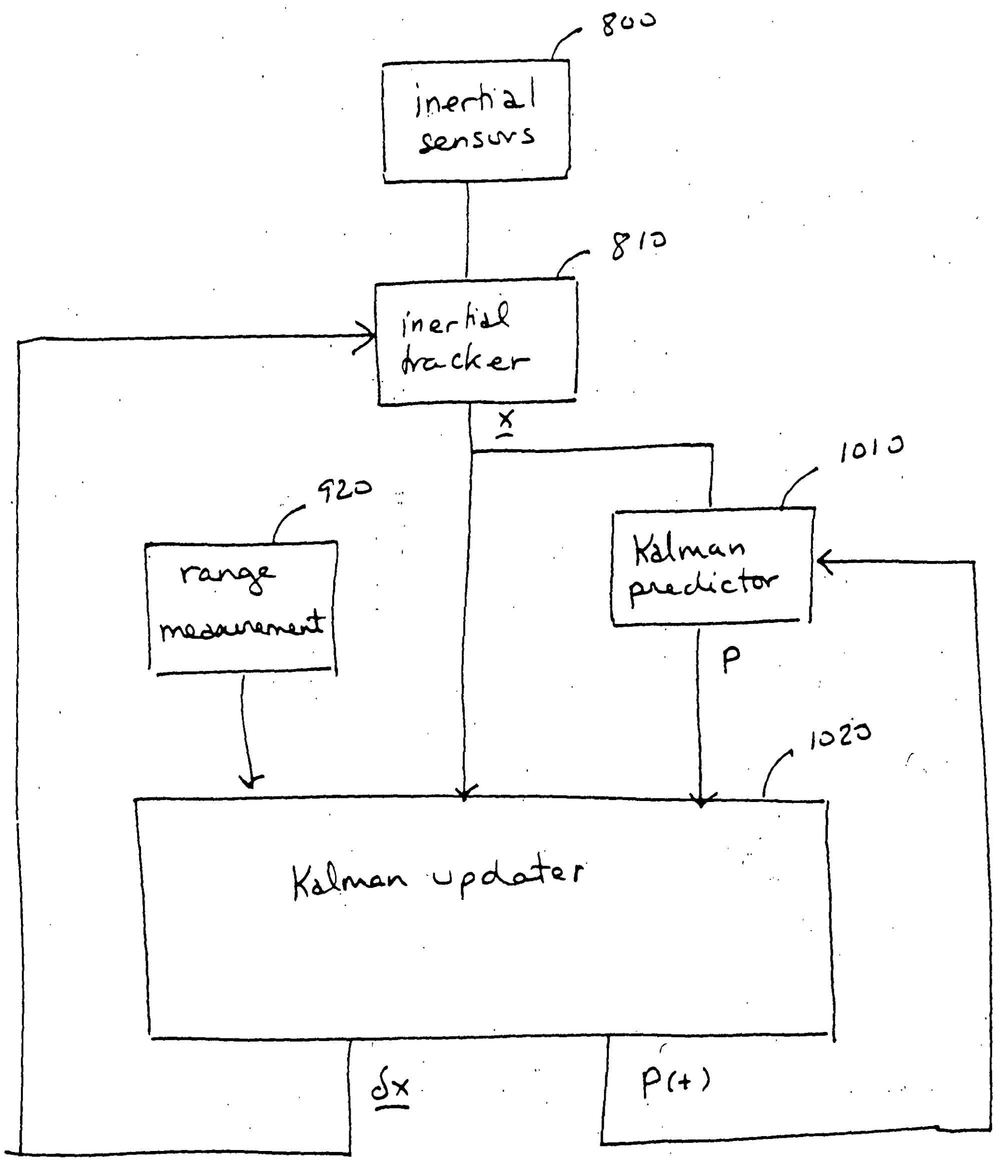
800
inertial sensors
810
inertial tracker
x
1010
920
range measurement
Kalman predictor
P
1020
Kalman updater
δx
P(+)

Fig. 10

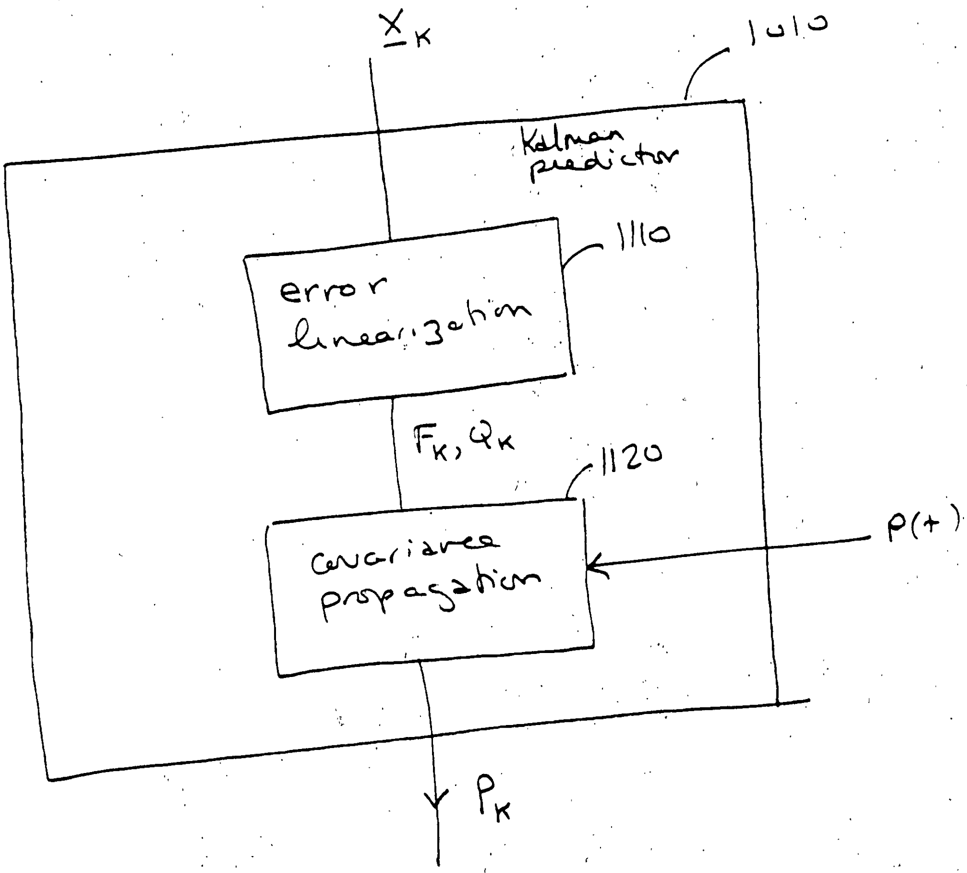
$\underline{x}_K$
1010
Kalman predictor
error linearization
1110
F_K, Q_K
1120
covariance propagation
P(+)
P_K

Fig. 11

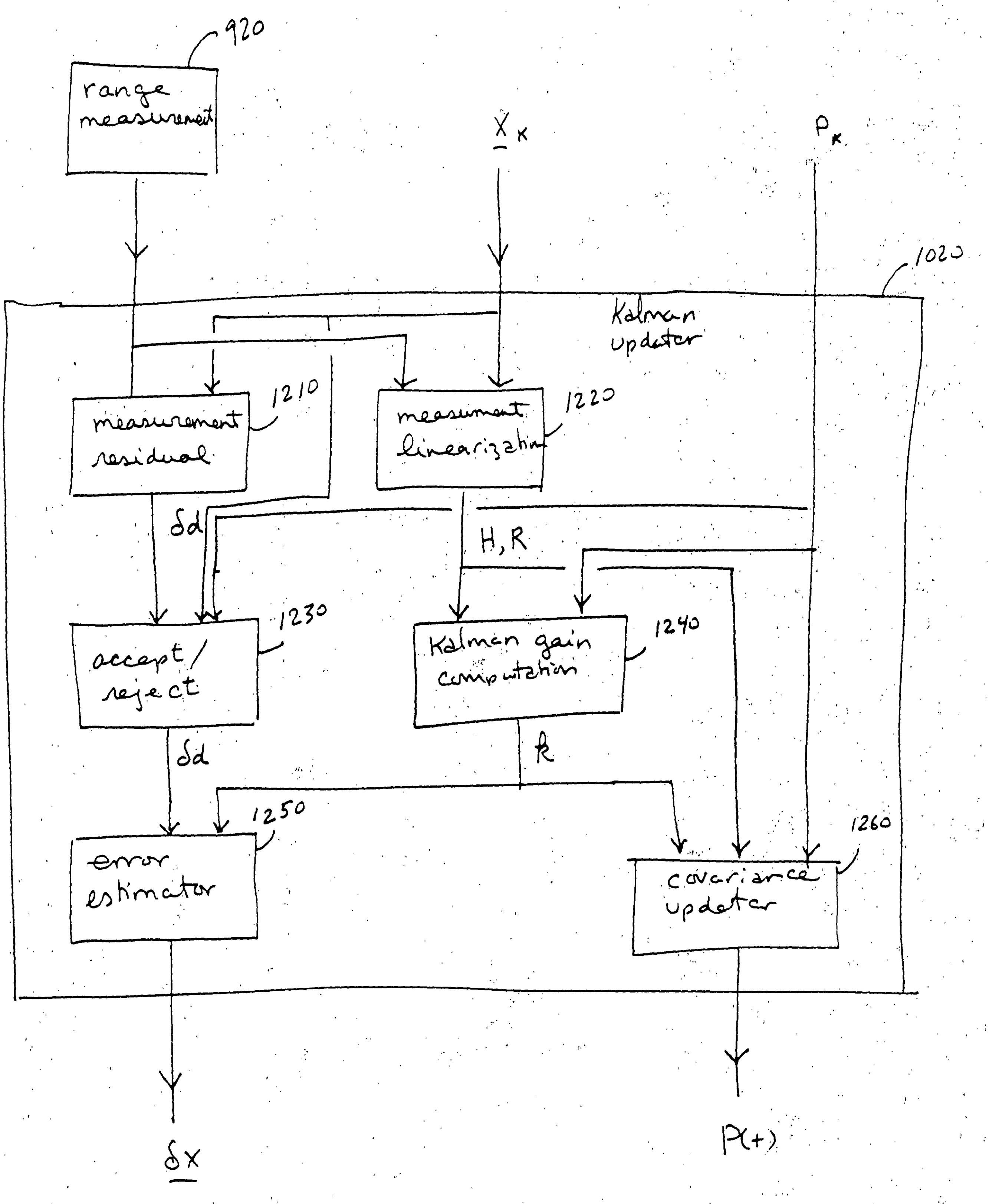
920
range measurement
$\underline{X}_K$
P_K
1020
Kalman updater
measurement residual
1210
measurement linearization
1220
δd
H, R
accept / reject
1230
Kalman gain computation
1240
δd
k
error estimator
1250
covariance updater
1260
$\underline{\delta x}$
P(+)

Fig. 12

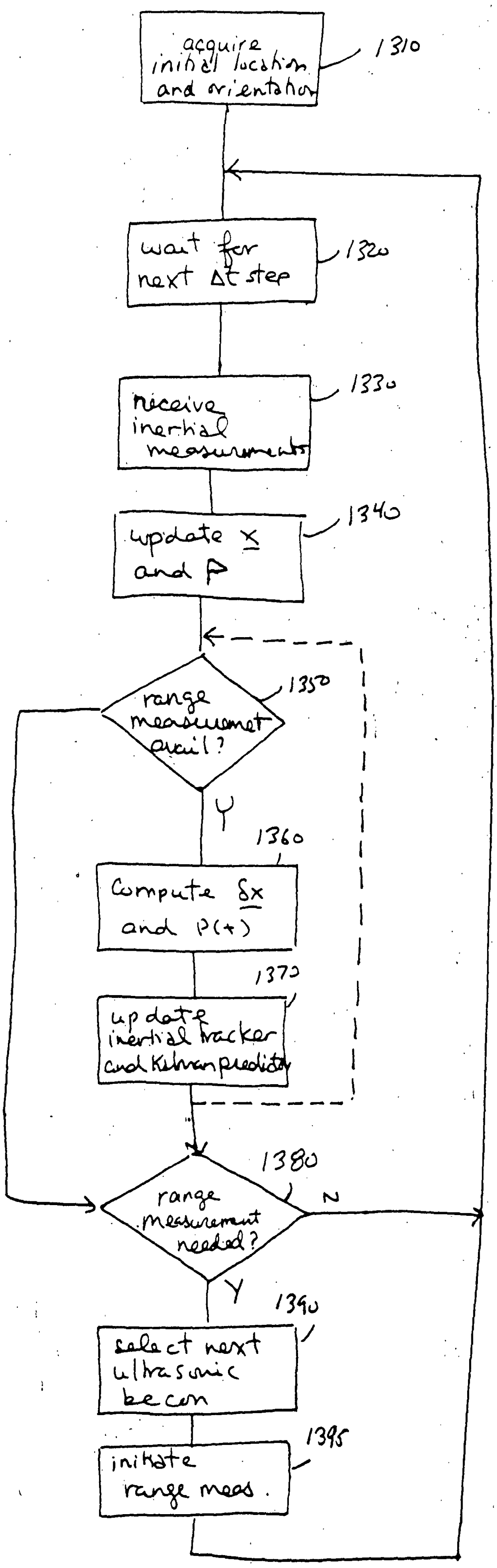
acquire initial location and orientation
1310
wait for next Δt step
1320
receive inertial measurements
1330
update x and P
1340
range measurement avail?
1350
Y
1360
Compute δx and P(+)
1370
update inertial tracker and Kalman predictor
range measurement needed?
1380
N
Y
1390
select next ultrasonic beacon
1395
initiate range meas.

Fig. 13

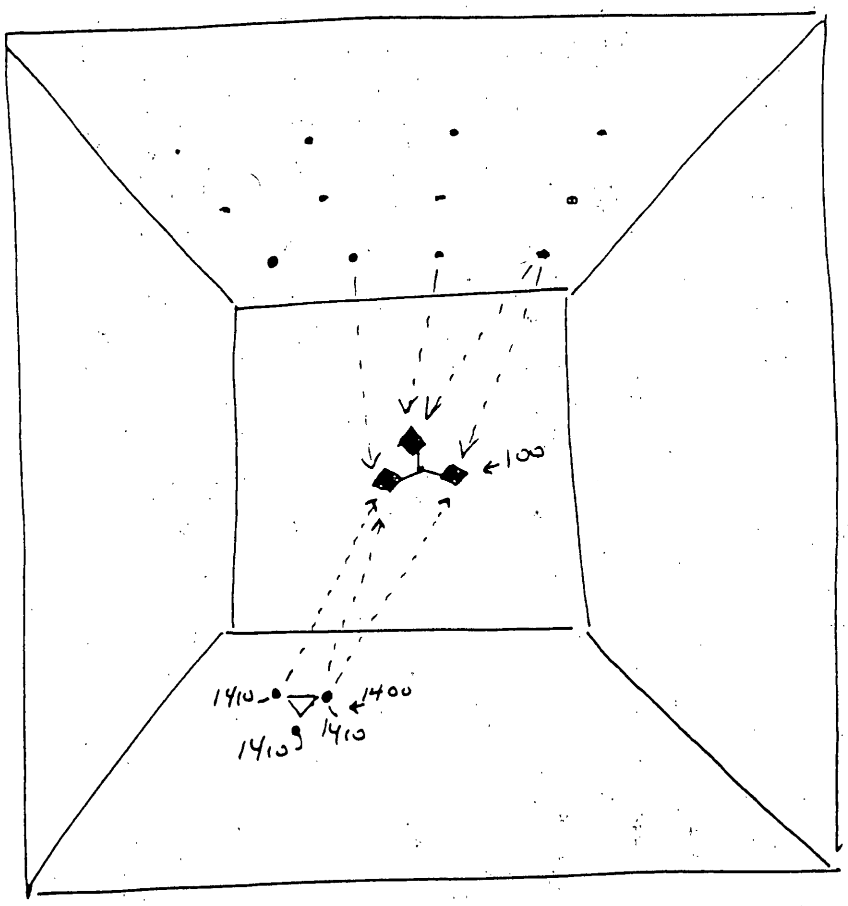

Fig. 14a

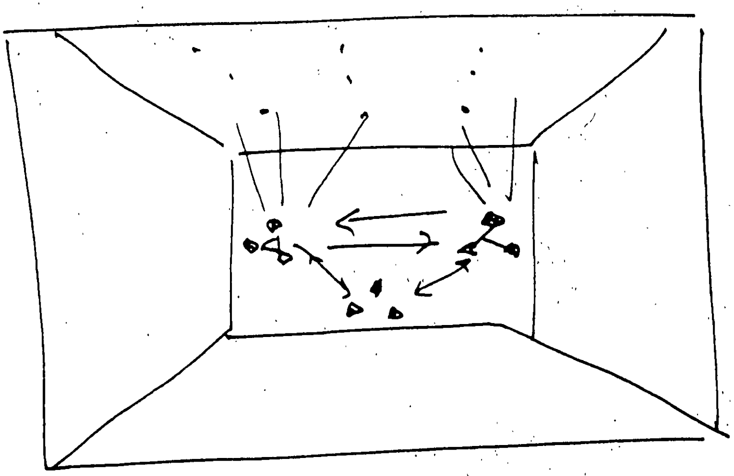

Fig 14b

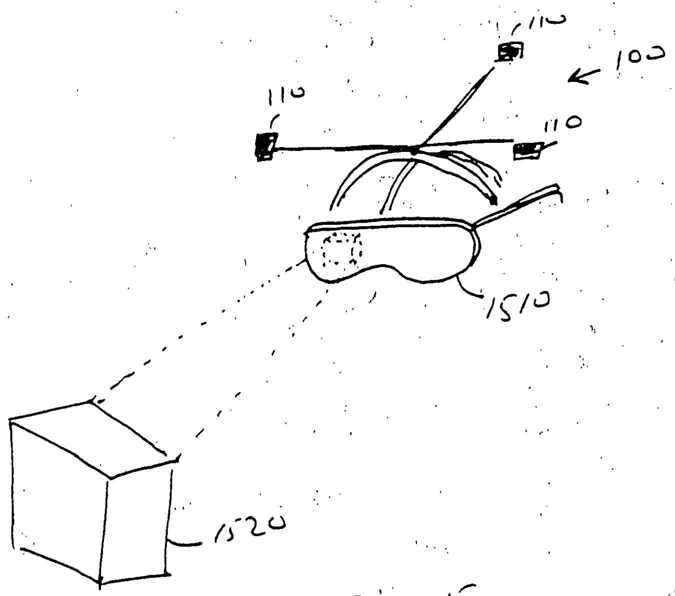

Fig. 15

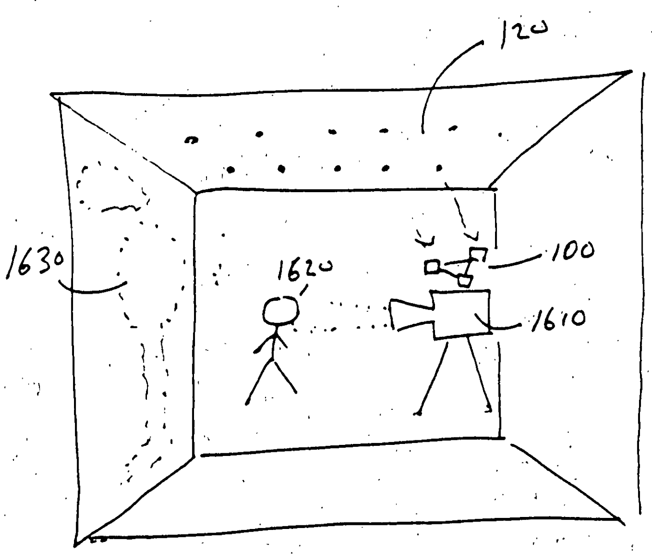

Fig. 16

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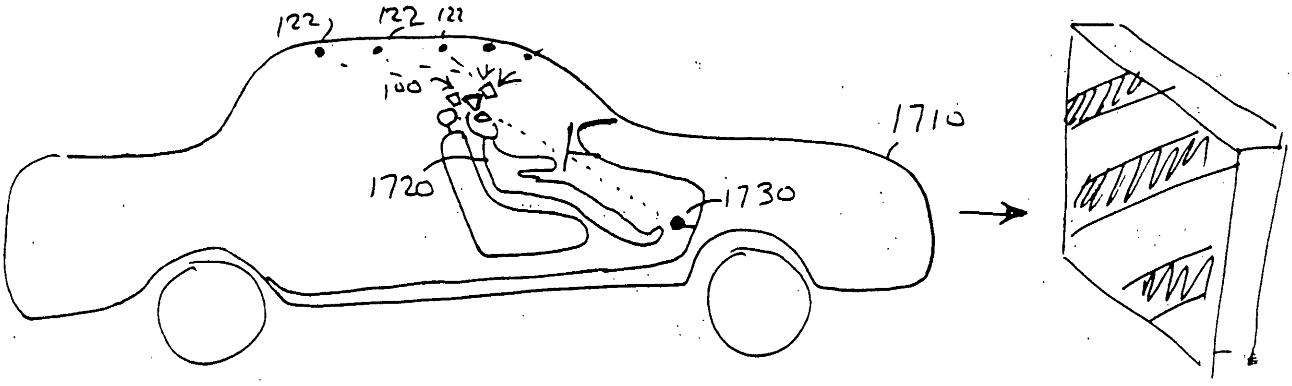

Fig. 17

Transaction History Date 1998-05-20
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

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Washington, D.C. 20231

APPLICATION NUMBER	FILING/RECEIPT DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO./TITLE
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

DATE MAILED: [illegible]

NOTICE TO FILE MISSING PARTS OF APPLICATION
Filing Date Granted

An Application Number and Filing Date have been assigned to this application. The items indicated below, however, are missing. Applicant is given TWO MONTHS FROM THE DATE OF THIS NOTICE within which to file all required items and pay fees required below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a). **If any of items 1 or 3 through 5 are indicated as missing, the SURCHARGE set forth in 37 CFR 1.16(e) of ☐ $65.00 for a small entity in compliance with 37 CFR 1.27, or ☑ $130.00 for a non-small entity, must also be timely submitted in reply to this NOTICE to avoid abandonment.**

If all required items on this form are filed within the period set above, the total amount owed by applicant as a ☐ small entity (statement filed) ☑ non-small entity is $____________.

☐ 1. The statutory basic filing fee is:
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Applicant must submit $__________ to complete the basic filing fee and/or file a small entity statement claiming such status (37 CFR 1.27).

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$________ for ________ independent claims over 3.

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Applicant must either submit the additional claim fees or cancel additional claims for which fees are due.

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- ☐ does not cover the newly submitted items.
- ☐ does not identify the application to which it applies.
- ☐ does not include the city and state or foreign country of applicant's residence.

An oath or declaration in compliance with 37 CFR 1. 63, including residence information and identifying the application by the above Application Number and Filing Date is required.

☐ 4. The signature(s) to the oath or declaration is/are by a person other than inventor or person qualified under 37 CFR 1.42, 1.43 or 1.47.
A properly signed oath or declaration in compliance with 37 CFR 1.63, identifying the application by the above Application Number and Filing Date, is required.

☑ 5. The signature of the following joint inventor(s) is missing from the oath or declaration:
____
An oath or declaration in compliance with 37 CFR 1.63 listing the names of all inventors and signed by the omitted inventor(s), identifying this application by the above Application Number and Filing Date, is required.

☐ 6. A $50.00 processing fee is required since your check was returned without payment (37 CFR 1.21(m)).

☐ 7. Your filing receipt was mailed in error because your check was returned without payment.

☐ 8. The application does not comply with the Sequence Rules.
See attached "Notice to Comply with Sequence Rules 37 CFR 1.821-1.825."

☐ 9. OTHER: ____________________

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PART 3 - OFFICE COPY

FORM PTO-1533 (REV.9-97)

#21

OIPE
SEP 24 1998
JC42
PATENT & TRADEMARK OFFICE

PATENT
ATTORNEY DOCKET NO. 09970/002001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No.: 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit:
Examiner:

Assistant Commissioner for Patents
Washington, DC 20231

PETITION FOR TWO-MONTH EXTENSION OF TIME

Pursuant to 37 C.F.R. §1.136, applicants hereby petition that the period for response to the Notice to File Missing Parts mailed May 20, 1998, be extended for two months to and including September 21, 1998, inasmuch as September 20, 1998 was a Sunday.

Enclosed is a check for $ 400.00 for the required fee. Please apply any other charges or any credits to our deposit account number 06-1050.

Respectfully submitted,

Date: 9/21/98

Van Robin Rohlicek
J. Robin Rohlicek
Reg. No. 43,349

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804

Telephone: 617/542-5070
Facsimile: 617/542-8906
330586.B11

10/01/1998 MGORDON 00000022 09062442
02 FC:116 400.00 OP

Date of Deposit September 21, 1998

I hereby certify under 37 CFR 1.8(a) that this correspondence is being deposited with the United States Postal Service as **first class mail** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

$ SECTOR

#3

PATENT
ATTORNEY DOCKET NO. 09970/002001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No.: 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit:
Examiner:

Assistant Commissioner for Patents
Washington, DC 20231

Attention: Box Missing Parts

RESPONSE TO NOTICE TO FILE MISSING PARTS OF APPLICATION

Responsive to the Notice to File Missing Parts of Application under 37 CFR 1.53(d) mailed May 20, 1998 (a copy of which is enclosed), Applicant as a large entity submits herewith the following:

A Combined Declaration and Power of Attorney in compliance with 37 CFR 1.63.

Payment of the surcharge of $ 130.00 for late filing of the declaration.

It is understood that this perfects the application and no additional papers or filing fees are required.

Date of Deposit September 21, 1998

I hereby certify under 37 CFR 1.8(a) that this correspondence is being deposited with the United States Postal Service as **first class mail** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Matthew Doherty

If there are any other charges, or any credits, please apply them to Deposit Account No. 06-1050.

Respectfully submitted,

Date: 9/21/98

J. Robin Rohlicek
J. Robin Rohlicek
Reg. No. 43,349

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804

Telephone: 617/542-5070
Facsimile: 617/542-8906
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OIPE SEP 2 4 1998 JC42 PATENT & TRADEMARK OFFICE

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APPLICATION NUMBER	FILING/RECEIPT DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO./TITLE
09/062,442	04/17/98	FOXLIN E	09970002001

0362/0520

DAVID L FEIGENBAUM
FISH & ROBINSON PC
225 FRANKLIN STREET
BOSTON MA 02110-2804

NOT ASSIGNED

3737

DATE MAILED: 05/20/98

NOTICE TO FILE MISSING PARTS OF APPLICATION
Filing Date Granted

An Application Number and Filing Date have been assigned to this application. The items indicated below, however, are missing. Applicant is given TWO MONTHS FROM THE DATE OF THIS NOTICE within which to file all required items and pay fees required below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a). **If any of items 1 or 3 through 5 are indicated as missing, the SURCHARGE set forth in 37 CFR 1.16(e) of ☐ $65.00 for a small entity in compliance with 37 CFR 1.27, or ☑ $130.00 for a non-small entity, must also be timely submitted in reply to this NOTICE to avoid abandonment.**

If all required items on this form are filed within the period set above, the total amount owed by applicant as a ☐ small entity (statement filed) ☑ non-small entity is $ 130.00 .

☐ 1. The statutory basic filing fee is:
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Applicant must submit $ ______ to complete the basic filing fee and/or file a small entity statement claiming such status (37 CFR 1.27).

☐ 2. Additional claim fees of $______, including any multiple dependent claim fees, are required.
$______ for ______ independent claims over 3.
$______ for ______ dependent claims over 20.
$______ for multiple dependent claim surcharge.
Applicant must either submit the additional claim fees or cancel additional claims for which fees are due.

☐ 3. The oath or declaration:
☐ is missing or unexecuted.
☐ does not cover the newly submitted items.
☐ does not identify the application to which it applies.
☐ does not include the city and state or foreign country of applicant's residence.
An oath or declaration in compliance with 37 CFR 1.63, including residence information and identifying the application by the above Application Number and Filing Date is required.

☐ 4. The signature(s) to the oath or declaration is/are by a person other than inventor or person qualified under 37 CFR 1.42, 1.43 or 1.47.
A properly signed oath or declaration in compliance with 37 CFR 1.63, identifying the application by the above Application Number and Filing Date, is required.

☑ 5. The signature of the following joint inventor(s) is missing from the oath or declaration:
1st Mahmood Amirah
An oath or declaration in compliance with 37 CFR 1.63 listing the names of all inventors and signed by the omitted inventor(s), identifying this application by the above Application Number and Filing Date, is required.

☐ 6. A $50.00 processing fee is required since your check was returned without payment (37 CFR 1.21(m)).
☐ 7. Your filing receipt was mailed in error because your check was returned without payment.
☐ 8. The application does not comply with the Sequence Rules.
See attached "Notice to Comply with Sequence Rules 37 CFR 1.821-1.825."
☐ 9. OTHER: ______

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10/01/1998 HGORDON 00000022 09062442 01 FC:105 130.00 OP

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09/21/98 12:59 FAX ☑002

09/18/98 FRI 10:55 FAX 1617 ☑002

PATENT
ATTORNEY DOCKET NO: 09970/002001

COMBINED DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled MOTION TRACKING SYSTEM, the specification of which

☐ is attached hereto.
■ was filed on April 17, 1998 as Application Serial No. 09/062,442.
☐ was described and claimed in PCT International Application No. ______________ filed on ______________ and as amended under PCT Article 19 on ______________.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose all information I know to be material to patentability in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby appoint the following attorneys and/or agents to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: David L. Feigenbaum, Reg. No. 30,378; and J. Robin Rohlicek, Reg. No. P-43,349.

Address all telephone calls to David L. Feigenbaum at telephone number 617/542-5070.

Address all correspondence to David L. Feigenbaum, Fish & Richardson P.C., 225 Franklin Street, Boston, MA 02110-2804.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patents issued thereon.

Full Name of Inventor: Eric M. Foxlin

Inventor's Signature: Eric Foxlin Date: 9/18/98

Residence Address: 285 Highland Avenue, Arlington, MA 02174

Citizen of: U.S.A.

Post Office Address: 285 Highland Avenue, Arlington, MA 02174

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OIPE JC37
APR 19 1999
PATENT & TRADEMARK OFFICE

GR3737
#51 Prior Art

PATENT
ATTORNEY DOCKET NO. 01997/238001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No.: 09/062,442
Filed : April 17, 1998
Title : MOTION TRACING SYSTEM

Art Unit: 3737
Examiner:

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TECHNOLOGY CENTER 3700

Assistant Commissioner for Patents
Washington, DC 20231

<u>INFORMATION DISCLOSURE STATEMENT</u>

Applicant submits the references listed on the attached form PTO 1449, copies of which are enclosed.

Prior to April 17, 1998, InterSense, Inc. (previously named Angularis Inertial Technologies) had developed inertial tracking systems, some of which used both inertial and acoustic measurements. These systems included:

> <u>Angularis VR-360 Inertial Tracking System</u>. The system in reference AK included an integrated inertial orientation tracker. On page 2 of the brochure a "Hybrid 6-DOF Capability" is described. The described capability was intended to use an external ultrasonic position tracker that would be connected to an RS-232 input jack of the VR-360 by the user. Ultrasonic position data would then be "used only for positional drift compensation." A system that provided this hybrid 6-DOF capability was sold in 1996 to the Naval Postgraduate School.

Date of Deposit April 16, 1999

I hereby certify under 37 CFR 1.8(a) that this correspondence is being deposited with the United States Postal Service as **first class mail** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Lisa G Gray
Lisa G Gray

InterSense IS-300 Precision Motion Tracker. The IS-300 (reference AL) included essentially the same capabilities as the VR-360. A version of the IS-300, as described in the brochure, was shown at a trade show in 1996. A proposal (reference AM) provided by InterSense on October 28, 1996, for a six degree-of-freedom tracking system based on the IS-300 which was to use ultrasonic measurements to correct positional drift. This proposal was not accepted.

Virtual Vision Development Project. InterSense, Inc. began development of a tracking system for Virtual Vision, Inc., of Redmond, Washington, in March 1997. Virtual Vision made incremental payments to Intersense for services performed based on achievement of engineering milestones and delivery of progress reports. These payments included payments invoiced on April 11, 1997, for milestones achieved on March 7, 1997, and April 3, 1997. A first working prototype of the system was completed on April 17, 1997, and delivered to Virtual Vision, Inc. on April 18, 1997, at which time Virtual Vision made a payment to Intersense for the delivered prototype. Features of the delivered first prototype included an inertial tracker, an ultrasonic range finder used to correct positional and orientation drift, and a constellation of addressable ultrasonic transponders used to make range measurements from the tracking system. Intersense continued to work

on the system to incorporate new ultrasonic range finders, which overcame some limitations of the transponders used in the first prototype, to miniaturize the system, and to improve the software algorithms used in the system.

<u>InterSense IS-900CT Camera Tracker</u>. The IS-900CT (reference AO) was demonstrated and the brochure was distributed publicly by InterSense Inc. in July 1997 at the SIGGRAPH '97 conference. The IS-900CT used an inertial tracker with ultrasonic range measurements from a constellation of addressable ultrasonic transponders to correct position and orientation drift.

This statement is being filed before the receipt of a first office action on the merits. Please apply any charges or credits to Deposit Account No. 06-1050.

Respectfully submitted,

Date: 4/16/99

J Robin Rohlicek

J. Robin Rohlicek
Reg. No. 43,349

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804

Telephone: 617/542-5070
Facsimile: 617/542-8906

302846.B11

Sheet 1 (A) of 1

SUBSTITUTE FORM PTO-1449 (MODIFIED) INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Use several sheets if necessary) (37 CFR 1.98(b))	U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE
ATTY. DOCKET NO. 01997/238001	SERIAL NO. 09/062,442
APPLICANT Eric M. Foxlin	
FILING DATE April 17, 1998	GROUP 3736

OIPE JC37 APR 19 1999 PATENT & TRADEMARK OFFICE

U.S. PATENT DOCUMENTS

EXAMINER INITIAL		PATENT NUMBER	ISSUE DATE	PATENTEE	CLASS	SUBCLASS	FILING DATE IF APPROPRIATE
CAM	AA	3630079	12/28/71	Hughes et al.	73	178	
CAM	AB	4315326	02/09/82	Chase, Jr.	367	134	
CAM	AC	4408488	10/11/83	Marshall	73	170A	
CAM	AD	4928263	05/22/90	Armstrong et al.	367	118	
CAM	AE	5412619	05/02/95	Bauer	367	128	
CAM	AF	5645077	07/08/97	Foxlin	128	774	

OTHER DOCUMENTS (Including Author, Title, Date, Place of Publication)

CAM	AG	Brittan, "Kowning Where Your Head Is At," Technology Review, February/March 1995
CAM	AH	Foxlin, "Inertial Head-Tracker Sensor Fusion by Complimentary Separate-Bias Kalman Filter," Proc. VRAIS 1996
CAM	AI	Hollands, "Sourcelss Trackers," Technology Review, 4(3):23-27, 1995
CAM	AJ	Sowizral and Barnes, "Tracking Position and Orientation in a Large Volume," IEEE, pp. 132-139, 1993
CAM	AK	Angularis VR-360 Inertial Tracking System Brochure, Nov. 1995
CAM	AL	InterSense IS-300 Precision Motion Tracker Brochure, 1996
CAM	AM	Proposal for tracking system, Oct. 1996
CAM	AN	Intersense IS-600 Precision Motion Tracker Brochure, May 1997
CAM	AO	Intersense IS-900CT Camera Tracker Brochure, July 1997

EXAMINER Charles Marmor II	DATE CONSIDERED 6/2/99

EXAMINER: Initial citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

Substitute Disclosure Form (PTO-1449)

368656.B11

Other Prior Art

According to the information contained in form PTO-1449 or PTO-892, there are one or more other prior art/non-patent literature documents missing from the original file history record obtained from the United States Patent and Trademark Office. Upon your request we will attempt to obtain these documents from alternative resources. Please note that additional charges will apply for this service.

Knowing Where Your Head Is At

Links related to this article

You can immerse yourself in a state-of-the-art virtual-reality system, but no matter how gripping the illusion of flying an F-14 or touring a skyscraper, it is hard to escape the sensation that you are eight years old again and trying to read a comic book in the back seat of a moving vehicle.

The late-twentieth-century form of nausea known as simulator sickness arises from the jittery, swimming images that appear on most of the head-mounted displays used in virtual reality, and it is one of several virtual hang-ups that Eric Foxlin hopes to remedy. The problem is the tracker, the device that tells the computer where the user's head is and which way it is pointing. ``Computers have gotten faster and head-mounted displays have seen quite a bit of progress," says Foxlin, ``but we've been using essentially the same tracker - a magnetic system - for the last 10 years." Foxlin, a graduate student in the Sensory Communications Group at MIT's Research Laboratory of Electronics, has high hopes for a tracker based on inertial navigation.

Magnetic trackers sense the orientation of the user's head by measuring the distance between three emitter coils on the ceiling and three receiver coils on the headset. This process takes time - roughly 20 milliseconds for sampling the strengths of the signals, filtering out electromagnetic ``noise" from metal objects or electronic equipment in the same room, and performing calculations, says Foxlin. So when you turn your head, the virtual landscape you are viewing lags perceptibly. Add to this the shuddering of an image because of noise that eludes the filters, and it's time for a Dramamine.

No less serious a drawback is the lack of range. The radius of magnetic tracking systems is usually restricted to a few feet, says Foxlin - both because of health concerns over the effects of strong magnetic fields and because it would be impractical to clear a larger space of metal objects.

Although a few tracking systems use other technologies that avoid some of these shortcomings, Foxlin notes major flaws in each alternative. Acoustic systems, for example, replace magnetic devices with ultrasound emitters and receivers, protecting against interference from filing cabinets but not from echoes, jangling keys, or moving air. They are also constrained by the speed of sound. Optical systems, in which light-emitting diodes (LEDs) on the ceiling or headset signal their whereabouts to photodetectors, work only in a clear line of sight; they can be disrupted if a head tilts too far or a waving hand blocks the light. And they require elaborate equipment - a headset outfitted with four cameras and a ceiling studded with LEDs. Both acoustic and optical trackers suffer from range restrictions.

Enter the inertial tracker. With funding from NASA, Foxlin has spent the last three years developing a prototype that senses the orientation of a person's head the way an autopilot senses that of an airliner: with gyroscopes. Built into a palm-sized plastic block that attaches to the top of a head-mounted display are

three tiny solid-state gyros, one each to detect changes in pitch, yaw, and roll. Because the gyros measure angular changes directly, rather than in consultation with fixed emitters or receivers, Foxlin's tracker requires only a fraction of the processing time of conventional trackers - about one millisecond. It also is immune to the magnetic and acoustic interference that plagues trackers based on those forms of energy, so images are much steadier.

Another advantage of being self-contained is the tracker's virtually limitless range. Conducted in a large gymnasium or the great outdoors instead of within the narrow ambit of ultrasound detectors and other sensors, virtual reality could become an ideal training tool for sports, firefighting, or military maneuvers, Foxlin predicts.

Not by Gyros Alone

But gyroscopes by themselves are not a perfect solution. For one thing, the small, inexpensive solid-state devices in Foxlin's tracker are far less accurate than the bulky, high-priced gyros that guide planes and missiles; errors accumulate, causing the readings to drift three degrees off the mark each minute. To compensate, the tracker contains a compass and an inclinometer (basically a carpenter's level), which periodically take reference readings. Each time the user's head is still for a few moments, the tracker slowly resets itself to the orientation shown by the compass and the inclinometer.

A worse deficiency of gyros relative to conventional trackers is that they can't monitor your position - your actual location in space, as opposed to simply the angle of your head. If you hold your head still, you can take 10 paces forward wearing a gyro-based tracker, and the scene on your head-mounted display will remain stationary. In the inertial navigation systems used in various vehicles, position is tracked by means of accelerometers, which measure changes in speed - and indeed Foxlin plans to integrate such devices into his unit soon. But, he says, position is harder to calculate accurately than orientation; errors tend to multiply as acceleration is translated into velocity and as velocity is then translated into position.

While Foxlin works it all out, his system tracks the user's position by an age-old method: cheating. It incorporates an off-the-shelf acoustic beacon that calls to a trio of ceiling-mounted microphones. The miracle of triangulation does the rest. Although this approach reintroduces range limits and other problems his tracker was meant to solve, Foxlin finds it a satisfactory stopgap. ``It adds some jitter and delay," he says, ``but humans are much less sensitive to these when they affect position instead of orientation." - David Brittan

---

Links related to this article.
Suggest a link.

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Inertial Head-Tracker Sensor Fusion by a Complimentary Separate-Bias Kalman Filter

Eric Foxlin
Research Laboratory of Electronics
Massachusetts Institute of Technology

Abstract

Current virtual environment and teleoperator applications are hampered by the need for an accurate, quick-responding head-tracking system with a large working volume. Gyroscopic orientation sensors can overcome problems with jitter, latency, interference, line-of-sight obscurations, and limited range, but suffer from slow drift. Gravimetric inclinometers can detect attitude without drifting, but are slow and sensitive to transverse accelerations. This paper describes the design of a Kalman filter to integrate the data from these two types of sensors in order to achieve the excellent dynamic response of an inertial system without drift, and without the acceleration sensitivity of inclinometers.

1. Introduction

One of the key technological challenges in virtual environment, teleoperator, and augmented reality systems is head-tracking. Noise and latency in the data output by most current magnetic, acoustic, and optical head-tracking systems cause the objects in the virtual world to appear jittery and to swim about their correct stationary positions during head movements. Range limitations prohibit the use of VR for applications such as out-door operations training or building walkthroughs. Interference and distortions, particularly in magnetic systems, can cause user disorientation [1-3].

In order to overcome problems of limited range, portability, and line-of-sight restrictions, some kind of self-contained sourceless tracking system would be highly desirable. A purely inertial tracker would have the additional advantages of nearly instantaneous measurement, availability of motion derivatives for prediction, superb resolution/negligible jitter, and immunity to all forms of interference.

The operating principles for measuring orientation and position of a moving body using only gyroscopes and accelerometers have been well established in the field of Inertial Navigation Systems(INS) [4-9]. The variant called strapdown INS measures the orientation of a body by integrating the angular rates from three orthogonal rate gyros affixed to the body, starting from a known initial orientation. This orientation subsystem is referred to as an Attitude and Heading Reference System (AHRS). To get position, 3 linear accelerometers, also affixed to orthogonal axes of the moving body, measure the total acceleration vector of the body relative to inertial space. This acceleration vector can be converted from body coordinates to earth coordinates using the known instantaneous orientation of the body determined by the AHRS. Position is then obtained by subtracting off the effect of gravity from the measured acceleration and then performing double integration starting from a known initial position.

Drift in the determination of orientation by the AHRS results from gyro biases, which lead to a linear drift rate after single integration. If the startup bias can be measured and nulled, the worst case drift rate is determined by the bias stability, which ranges from about 1°/second for inexpensive silicon micromachined gyros to 0.001°/hour for sophisticated inertial navigation gyros. The best gyros of a practical size for head-tracking have a bias stability on the order of Earth's rotation rate of 15°/hour. Much less expensive and smaller are miniature vibrating element gyros with bias stabilities of several degrees/minute and worse. Drift in the measurement of linear displacement is a far more difficult problem due to the double integration of acceleration, and is not addressed in this paper.

An inertial head-tracker has been developed by the author at MIT, concentrating first on the more tractable problem of 3-DOF orientation tracking [10]. The first prototype consisted of three orthogonal angular rate sensors together with a two-axis fluid inclinometer for drift compensation. The outputs of the angular rate sensors were integrated to obtain orientation, and the orientation was occasionally reset by the fluid inclinome-

In Proceedings of VRAIS 96 March 30 - April 3, Santa Clara, California

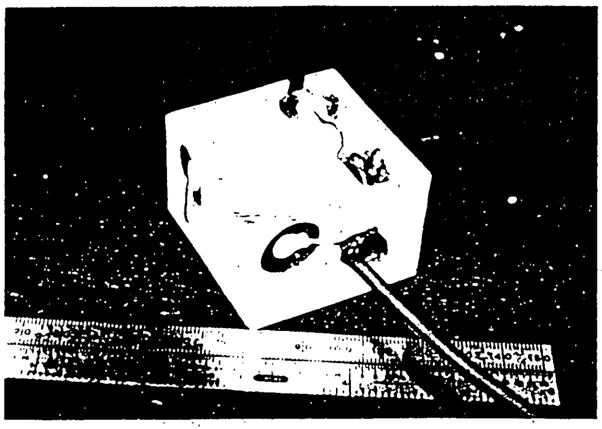

Figure 1: MIT inertial tracker 2nd prototype

ter to correct for the slow drift of the gyros. Due to the relatively high performance of the rate transducers used in that prototype, even this simple sensor fusion algorithm was able to achieve orientation tracking performance of <1 ms latency, 0.008° r.m.s. noise, and 0.5° absolute static and dynamic accuracy in pitch and roll [11]. At 1 lb., the prototype was still a little large for practical head-tracking applications.

A second prototype of the MIT Inertial Tracker, shown in Figure 1, has now been built which incorporates tiny low-cost solid-state rate gyros, a two-axis fluid inclinometer, and a two-axis fluxgate compass. It weighs only 3.5 ounces, can be comfortably worn on a head-mounted display, and uses low-cost sensors so that it can be developed into a competitive commercial head-tracking product. However, the miniature low-cost rate gyros have so much higher hysteresis, nonlinearity and bias instability that the simple ad hoc drift correction algorithm used in the previous prototype does not lead to sufficiently accurate results. This paper concerns the design of a more sophisticated sensor data fusion scheme, based on Kalman filtering, which makes the best use of all the data available from both types of sensors and thereby achieves a lower mean squared orientation estimation error than the ad hoc method. To be useful, the filter must be able to run in real time on an inexpensive 486-class microprocessor, so considerable effort is invested in formulating a minimum-order Kalman filter and implementing it efficiently.

The main contributions of this paper are 1) an analysis of the literature about related Kalman filter applications, 2) an exposition of the modeling decisions that were made to formulate the filter, which will help others to frame the questions necessary to apply Kalman filtering to similar problems, 3) an example of the use of Friedland's separate-bias Kalman filter formulation, which has not been previously applied in synthetic environment tracking work, and 4) a very effective adaptive algorithm for adjusting the Kalman filter parameters to the instantaneous motion characteristics. This paper focuses more on filter design and implementation than validation, and no effort is made to formulate an optimal filter and compare the performance of the reduced-order filter to the optimal filter in simulation.

2. Kalman filtering

Consider a dynamic system which can be modeled by a n-by-1 state vector $\mathbf{x}$ obeying a discrete-time (DT) evolution equation

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \mathbf{w}_k \tag{1}$$

where $\mathbf{A}$ is an n-by-n state transition matrix, $\mathbf{B}$ is an n-by-p matrix and $\mathbf{u}$ is a p-by-1 vector of known system inputs, and $\mathbf{w}$ is an n-by-1 process noise vector with covariance matrix $\mathbf{Q}_k$. (Note that lower-case bold letters, Greek or Roman, denote vectors, and upper-case bold letters denote matrices.) Suppose there are indirect measurements of the state vector available at each time k, and that they can be expressed as an m-by-1 measurement vector

$$\mathbf{y}_k = \mathbf{C}\mathbf{x}_k + \mathbf{v}_k \tag{2}$$

where $\mathbf{C}$ is an m-by-n system observation matrix, and $\mathbf{v}$ is an m-by-1 measurement noise vector with covariance $\mathbf{R}_k$. A Kalman filter is a recursive algorithm for computing an estimate $\hat{\mathbf{x}}$ of state which is optimal in the sense of least square error under certain circumstances. One form of the DT Kalman filter, used in Section 4.5, is

$$\hat{\mathbf{x}}_{k+1} = \mathbf{A}\hat{\mathbf{x}}_k + \mathbf{B}\mathbf{u}_k + \mathbf{K}_{k+1}(\mathbf{y}_{k+1} - \mathbf{C}\mathbf{A}\hat{\mathbf{x}}_k) \tag{3}$$

where the Kalman gain matrix $\mathbf{K}$ is computed from the estimation error covariance matrix, $\mathbf{P}$, according to

$$\mathbf{K}_k = \mathbf{P}_k\mathbf{C}^T\left[\mathbf{C}\mathbf{P}_k\mathbf{C}^T + \mathbf{R}_k\right]^{-1} \tag{4}$$

and $\mathbf{P}$ is updated according to the Ricatti equation:

$$\mathbf{P}_{k+1} = \mathbf{A}\left[\mathbf{I} - \mathbf{K}_k\mathbf{C}\right]\mathbf{P}_k\mathbf{A}^T + \mathbf{Q}_{k+1}. \tag{5}$$

The Kalman filter is very useful for combining data from several different indirect and noisy measurements to try to estimate variables which are not directly measurable. Thus, while the gyroscopes measure orientation by integrating angular rates, and the inclinometer and compass provide a different noisy and sloshy but drift-free measurement of orientation, the Kalman filter weights the two sources of information appropriately to make the best use of all the data from each. If the model in (1) and (2) is a simplification of the actual physical system, the resulting reduced-order Kalman filter (ROKF) will not be optimal, but will often perform almost as well as the full-order Kalman filter. This property is exploited in this paper without any attempt to evaluate the performance of the ROKF. If the system dynamics are nonlinear, it is possible to linearize about a nominal or actual trajectory and run a Kalman filter on the linearized system. This is

the basis of the extended Kalman filter (EKF) and the complimentary Kalman filter developed in Section 4.2. A discussion of Kalman filtering can be found in [12].

3. Literature analysis

In applying Kalman filtering to the inertial orientation tracking problem there is considerable freedom in system modeling - what physical variables to assign to the state vector **x**, what measurements are in the measurement vector **y**, and what matrices **A**, **B**, **C**, **Q**, and **R** most accurately describe the system given those choices. A literature search was conducted to see how other authors have used Kalman filters to estimate orientation from the outputs of 3 strapdown gyros. The 7 most relevant references found are reviewed in this section. Two come from vehicle navigation, two from robotics, and three from virtual environments.

An early maritime navigation work by Bona and Smay [13], summarized in [12], is of interest because it shows how to reset gyro biases based on indirect measurements (position errors that result from them) and provides a now-common Markov model of gyro bias evolution. The dynamic system model details how the position errors evolve in response to the gyro biases, and how the gyro bias Markov components evolve in response to the process noise.

The most relevant reference found in the aeronautics literature was Koifman and Merhav's description of an autonomously aided strapdown attitude reference system [14]. Here, an autopilot is created with three low-cost rate gyros with time-varying biases on the order of 0.1°/s. The measurements fed into the Kalman filter are from the three gyros, a magnetic compass, altimeter, and airspeed sensor. The state vector contains 16 elements: 3 linear velocities, 3 angular velocities, 3 orientation Euler angles, altitude, 3 wind gust velocity components and 3 gyro biases. The state transition matrix is obtained by linearizing the system differential equations which encompass the aircraft equations of motion as well as the kinematic Euler equations (6). In contrast to Bona and Smay, the gyro biases are considered piecewise constant, and the corresponding diagonal covariance elements are simply reset whenever a change detection algorithm suspects that the gyro biases may have changed. It is also instructive to note that the full order 16-dimensional system could not be run in real time, so they reduced the state to 11 elements and were then able to achieve about 20 updates per second with minimal loss in accuracy. The measurement vector consists of the three gyros and the airspeed sensor.

Barshan and Durrant-Whyte [15] investigated the use of a solid-state gyroscope for mobile robotics applications. They paid particular attention to the gyroscope error model, and came up with an exponential curve to fit the changes in bias as the gyroscope warms up. They then implemented a Kalman filter for estimating a single rotation angle Φ, with a state vector $\begin{bmatrix} \Phi & \dot{\Phi} & \ddot{\Phi} & \dddot{\Phi} & \varepsilon_{\Phi} & \varepsilon_{\dot{\Phi}} \end{bmatrix}^T$ and a state transition matrix that propagates the truth states $\Phi, \dot{\Phi}, \ddot{\Phi}, \dddot{\Phi}$ and error states $\varepsilon_{\Phi}, \varepsilon_{\dot{\Phi}}$ completely independently. The only system observation is the single rate gyro measurement, so the system is not observable, and the angular position error covariance grows unbounded. However, it is demonstrated that the gyro drift error grows at a rate 5 times slower when using the exponential gyro error model.

A paper on mobile robot attitude estimation by Vaganay et al [16] provides the only example in the literature in which gyroscope drift is compensated using two accelerometers, and is therefore particularly germane to this drift-free head-tracking application. The Kalman filter model is very unusual and results in a state vector of surprisingly low dimension. The integration of angular rates is done outside of the Kalman filter, and is treated as part of a measurement system that provides gyroscopically determined measurements of pitch and roll, θ_g and ψ_g, which are complimented by gravimetric measurements of θ and ψ from the accelerometers. The state contains θ and ψ and the pitch and roll drift rates, and the transition matrix used in the Kalman filter is just the identity. This is the leanest Kalman filter conceivable, as even the kinematics of Euler angle integration are not modeled, but the performance reported is nearly comparable to the other methods. No details are given about the determination of **Q** and **R**.

Azuma and Bishop developed a Kalman filter to use inertial sensors together with an optical head-tracker to predict head motion in HMD applications [17]. The approach is different from the preceding papers, and also from the application developed in this paper, because the gyroscope rate signals are not integrated to obtain orientation. Instead, the orientation is obtained from the optical head-tracker, and the angular rates are fused with this in the Kalman filter to yield improved predictions. The state vector contains a quaternion specifying orientation, the angular rates in body axes, and the angular accelerations in body axes. The measurement consists of the quaternion measured by the optical tracker, and the angular rates measured by the gyros. The **Q** and **R** matrices are determined off-line using Powell's method on prerecorded datasets to find the parameters that give the best performance. Prediction was accomplished by extrapolating forward in time, using the angular velocity and acceleration estimates in the state vector.

Emura and Tachi likewise used gyros to augment the dynamic performance of an existing head-tracker, but in this case the tracker was magnetic instead of optical [18, 19]. The state vector contains orientation (Euler angles in the first paper were replaced with a quaternion in the second) and angular velocities. The measurement vector measures all elements of the state, using a Polhemus magnetic tracker to measure orientation and gyros to measure the angular rates. A novel aspect of the Kalman filter structure is the use of two different types of measurement update step: a 3-dimensional measurement used most of the time, when only gyro data is available, and a 6-dimensional measurement used when the Polhemus data is available as well. Q and R were found empirically, using a high-precision mechanical tracker as a reference to measure remnant errors.

4. System modeling and filter design

4.1 State and measurement vectors

The first step in modeling is to decide what to put in the state and measurement vectors. Since the basic purpose of the Kalman filter is to estimate orientation, it is a given that it will be included in the state vector. Indeed, all the authors except [13] include it, although they are split between quaternion and Euler angle representations. In the interest of smaller state dimension (i.e. faster computation), this implementation uses Euler angles. The aeronautics convention is used, where ϕ, θ, and ψ, called yaw, pitch and roll respectively, represent positive rotations about the z, y, and x body axes in turn, with the positive x-axis pointing forward, positive y pointing right, and positive z pointing down. There is a singularity in the Euler angle representation at $\theta = \pm 90°$, but this was not found to produce any noticeable disturbances in practice.

All the remaining references except [16] also include angular rates in the state vector and gyroscopic angular rate measurements in the measurement vector. This is very natural, as it allows the Euler angle integration kinematics [20],

$$\dot{\theta}(t) = \mathbf{W}_B(\theta(t))\,\omega(t)$$

$$\theta(t) \equiv \begin{bmatrix} \psi(t) \\ \theta(t) \\ \phi(t) \end{bmatrix}, \quad \omega(t) \equiv \begin{bmatrix} \omega_x(t) \\ \omega_y(t) \\ \omega_z(t) \end{bmatrix} \tag{6}$$

$$\mathbf{W}_B(\theta(t)) \equiv \begin{bmatrix} 1 & \sin\psi(t)\tan\theta(t) & \cos\psi(t)\tan\theta(t) \\ 0 & \cos\psi(t) & -\sin\psi(t) \\ 0 & \sin\psi(t)/\cos\theta(t) & \cos\psi(t)/\cos\theta(t) \end{bmatrix}$$

to be incorporated into the system dynamics model, and allows the gyro measurements to be utilized in the obvious way - as measurements. However, while it is obvious from (6) how the derivatives of the orientation state elements will be computed from the state, how shall the derivatives of the angular velocity components depend on state? Some authors [18, 19] simply assume zero dependence, i.e. constant angular rates. Some process noise is added to the angular accelerations to allow for non-constant angular rates, but in reality the angular accelerations would not be very much like white noises, so this model cannot be very optimal. Other authors [15, 17] augment the state vector with $\dot{\omega}$, which changes the model to an assumption of constant angular acceleration. The difference between the true $\dot{\omega}$ and the assumed $\dot{\omega} = 0$ is closer to white noise. Further derivatives, as in [15], make the model even more accurate, but lead to an unreasonably large state vector.

For most accurate estimation, the equations of motion of the body being tracked should be included in the system dynamics model (1). For example, in [14] the angular accelerations of the aircraft depend precisely, through well-known aircraft equations of motion, on quantities in the state vector and aileron positions, which are known inputs. Unfortunately, head accelerations are driven by muscle forces - an unknown input - so head dynamics are not modeled in the current system.

In inertial navigation applications, such as [13-15], gyro bias terms are usually included in the state vector. This is very important where the only aiding comes from sparse or indirect sources such as occasional position fixes. In this case, it is desired to milk as much accuracy as possible out of the gyro integration algorithm, and time-varying gyro biases are the largest source of error. Our state vector is therefore augmented with the three gyro bias terms $\delta\omega_x$, $\delta\omega_y$, and $\delta\omega_z$.

4.2 Complimentary Kalman filter

While most of the references above used a Kalman filter to directly estimate the state variables of orientation and it's derivatives, it is common in inertial navigation systems to instead use a complimentary Kalman filter which operates only on the errors in those primary state variables [12].

The direct Kalman filter block diagram in Figure 2 has ω measured by the gyros and θ measured by the aiding sensors all as measurement inputs. The Euler angle integration of (6) is then accomplished as part of the prediction step inside the Kalman filter block. The complimentary Kalman filter is shown in Figure 3. Here, the integration of the Euler angles is performed outside of the Kalman filter, in the block labeled "attitude computation". One advantage of this structure is that it guaran-

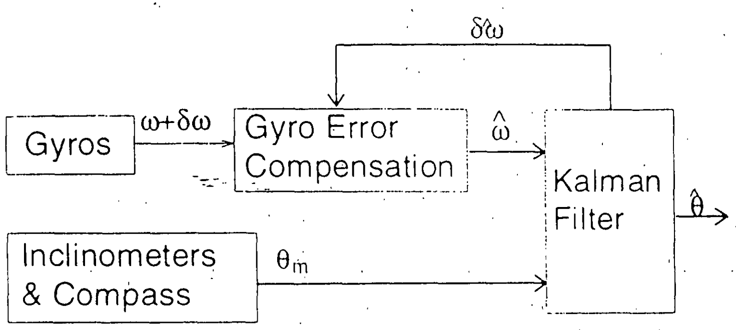

Figure 2: Direct Kalman filter for orientation

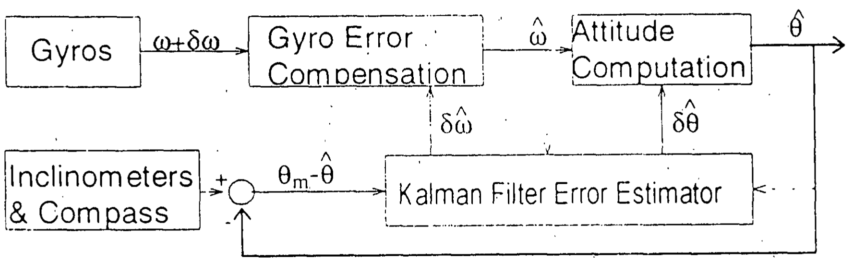

Figure 3: Complimentary Kalman filter for orientation

tees that the rapid dynamic response of the inertial system will not be compromised by the Kalman filter. Another advantage is that the gyro rates are not treated as measurements, so it is unnecessary to include ω in the state vector. Since the head dynamics are not being modeled in this implementation, ω is excess baggage, and by removing it from $\mathbf{x}$ the dimension is reduced from 9 to 6, with more than a three-fold computational savings. The following sections, therefore, will strive to develop a complimentary Kalman filter to estimate

$$\delta \mathbf{x} = \begin{bmatrix} \delta\theta \\ \delta\omega \end{bmatrix} \equiv \begin{bmatrix} \delta\psi & \delta\theta & \delta\phi & \delta\omega_x & \delta\omega_y & \delta\omega_z \end{bmatrix}^T \quad (7)$$

using

$$\delta \mathbf{y} = \begin{bmatrix} \psi_{inclinometer} - \hat{\psi} & \theta_{inclinometer} - \hat{\theta} & \phi_{compass} - \hat{\phi} \end{bmatrix}^T \quad (8)$$

as the measurements, where $\delta\theta$ represents the error in the output of the attitude computer, and $\delta\omega$ represents the gyro biases.

4.3 DT nonlinear attitude computation

A Kalman filter which operates on the errors of the INS attitude computer must mimic the noise-free error dynamics of the attitude computation. This section derives the attitude integration algorithm, Section 4.4 linearizes the attitude algorithm to obtain the error dynamics, and Section 4.5 describes a complimentary EKF to operate on the errors of the attitude computation, with the computational complexity of the EKF reduced by applying Friedland's separate bias formulation.

The continuous-time (CT) nonlinear differential equation which the attitude computer must integrate was given in (6). To derive the DT attitude computation from it, it is useful to approximate the evolution of $\theta(t)$ over a short time interval by its Taylor series expansion

$$\theta(t+\Delta t) = \theta(t) + \dot{\theta}(t)\,\Delta t + \ddot{\theta}(t)\frac{\Delta t^2}{2} + \ldots \quad (9)$$

The number of terms which must be retained depends on the size of Δt. For a first order integration algorithm (retaining only the first two terms), the error per step will be mostly due to the third term, which is of order $\omega^2 \Delta t^2 / 2$. Therefore,

$$\text{error rate} \approx \frac{1}{2}\omega^2 \Delta t .$$

For typical peak head velocities of about 6 radians/sec and a timestep of 0.003 sec, this yields an error rate of about .05 rad/s (about 3°/s) which is unacceptable. Retaining the third term, the error rate will be dominated by the fourth term, or order $\omega^3 \Delta t^3 / 6$, so

$$\text{error rate} \approx \frac{1}{6}\omega^3 \Delta t^2 .$$

For the same ω and Δt the error rate would be about 0.0003 rad/s, or about 1°/min. Since the low-cost gyros are unlikely to have performance much better than this, a second order integration algorithm was selected.

Differentiating (6) by the chain rule for partial derivatives results in

$$\ddot{\theta}(t) = \frac{\partial}{\partial \theta}\left[\mathbf{W}_B(\theta(t))\ \omega(t)\right] \dot{\theta}(t) + \frac{\partial}{\partial \omega}\left[\mathbf{W}_B(\theta(t))\ \omega(t)\right] \dot{\omega}(t) \quad (10)$$

Defining (with time indices suppressed for brevity)

$$\mathbf{V}_B(\theta,\omega) \equiv \frac{\partial}{\partial \theta}\left[\mathbf{W}_B(\theta)\omega\right] =$$

$$\begin{bmatrix} \frac{\cos\psi\sin\theta}{\cos\theta}\omega - \frac{\sin\psi\sin\theta}{\cos\theta}\omega & \frac{\sin\psi}{\cos^2\theta}\omega + \frac{\cos\psi}{\cos^2\theta}\omega & 0 \\ -\sin\psi\,\omega - \cos\psi\,\omega & 0 & 0 \\ \frac{\cos\psi}{\cos\theta}\omega - \frac{\sin\psi}{\cos\theta}\omega & \frac{\sin\psi\sin\theta}{\cos^2\theta}\omega + \frac{\cos\psi\sin\theta}{\cos^2\theta}\omega & 0 \end{bmatrix} \quad (11)$$

and approximating the derivative of $\omega(t)$ by its first difference,

$$\dot{\omega}(t) \approx \frac{\omega(t+\Delta t)-\omega(t)}{\Delta t} \qquad (12)$$

and substituting (11) and (12) into (10) yields

$$\begin{aligned} \ddot{\theta}(t) &= \mathbf{V}_B\big(\theta(t), \omega(t)\big)\, \mathbf{W}_B\big(\theta(t)\big)\, \omega(t) \\ &\quad + \mathbf{W}_B\big(\theta(t)\big) \frac{\omega(t+\Delta t)-\omega(t)}{\Delta t} \end{aligned} \qquad (13)$$

Plugging (6) and (13) into (9) and rearranging terms slightly leads to

$$\begin{aligned} \theta(t+\Delta t) &= \theta(t) + \mathbf{W}_B \frac{\omega(t)+\omega(t+\Delta t)}{2} \Delta t \\ &\quad + \mathbf{V}_B \mathbf{W}_B \omega(t) \frac{\Delta t^2}{2} \end{aligned} \qquad (14)$$

which is the second order DT integration step formula implemented in the attitude computer. Since Δt remains as an explicit parameter in this formula, it is unnecessary to have constant stepsize. This eliminates the difficulties of an interrupt driven program structure that would be necessary to have constant sampling rate data acquisition.

4.4 DT linearized error dynamics

Equation (14) defines a nonlinear state propagation function $\mathbf{f}_{\Delta t}$ for the system with state vector θ and input ω:

$$\theta(t+\Delta t) = \mathbf{f}_{\Delta t}\big(\theta(t), \omega(t), \omega(t+\Delta t), t\big) \qquad (15)$$

For the sake of obtaining an extended Kalman filter which can estimate both orientation errors and gyro biases, consider augmenting the state vector with ω and rewriting the system in the form

$$\begin{bmatrix} \theta(t+\Delta t) \\ \omega(t+\Delta t) \end{bmatrix} = \tilde{\mathbf{f}}_{\Delta t}\left(\begin{bmatrix} \theta(t) \\ \omega(t) \end{bmatrix} \right) + \mathbf{u}(t)$$

$$\tilde{\mathbf{f}}_{\Delta t}\left(\begin{bmatrix} \theta(t) \\ \omega(t) \end{bmatrix} \right) = \begin{bmatrix} \mathbf{f}_{\Delta t}\big(\theta(t), \omega(t), \omega(t+\Delta t), \Delta t\big) \\ \omega(t) \end{bmatrix} \qquad (16)$$

$$\mathbf{u}(t) = \begin{bmatrix} 0 \\ \omega(t+\Delta t) - \omega(t) \end{bmatrix}$$

where $\mathbf{u}(t)$ has been deviously chosen to make $\omega(t)$ evolve in accordance with the input history of the previous system. The system error dynamics can now be obtained by linearizing about the nominal trajectory $[\theta(t) \quad \omega(t)]^T$ to get

$$\begin{bmatrix} \delta\theta(t+\Delta t) \\ \delta\omega(t+\Delta t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \delta\theta(t) \\ \delta\omega(t) \end{bmatrix} \qquad (17)$$

where

$$\begin{aligned} \mathbf{A} &= \frac{\partial \mathbf{f}_{\Delta t}(t)}{\partial \theta(t)} = \mathbf{I} + \mathbf{V}_B \Delta t + \left[\mathbf{V}_B^2 + \left(\frac{\partial}{\partial \theta} \mathbf{V}_B \right) \mathbf{W}_B \omega \right] \frac{\Delta t^2}{2} \\ \mathbf{B} &= \frac{\partial \mathbf{f}_{\Delta t}(t)}{\partial \omega(t)} = \mathbf{W}_B \Delta t + \left[\mathbf{V}_B \mathbf{W}_B + \left(\frac{\partial}{\partial \omega} \mathbf{V}_B \right) \mathbf{W}_B \omega \right] \frac{\Delta t^2}{2} \end{aligned} \qquad (18)$$

and $\mathbf{0}$ and $\mathbf{I}$ are 3-by-3 zero and identity matrices. The vector partial derivatives of $\mathbf{V}_B$ are too messy to write out in full, but the computation is straightforward and can be carried out as follows: 1) form a "row vector" of the three matrices obtained by differentiating $\mathbf{V}_B$ with respect to the first, second and third elements of the vector in the denominator of the partial derivative; 2) multiply each of these three matrices by the r.h.s. vector $\mathbf{W}_B\omega$. This results in a "row vector of column vectors", i.e. a 3-by-3 matrix.

Equation (17) gives the state transition matrix for the linearized error dynamics of the augmented system. The angular velocity errors $\delta\omega$ are principally due to gyro biases, and will be interpreted simply as gyro biases from here on. The $\mathbf{A}$ and $\mathbf{B}$ submatrices can be interpreted as describing the influence of the orientation error and gyro biases at time t on the orientation error at time $t+\Delta t$. The effect of the matrix is fairly obvious; it basically mimics the attitude computation of (14) except that the input angular velocity is due to gyro biases and the output is therefore an orientation *error*. The growth of orientation error in the absence of angular rate errors is governed by the $\mathbf{A}$ matrix. To first order $\mathbf{A} = \mathbf{I} + \mathbf{V}_B \Delta t$. The identity term maintains the previously accrued error, and $\mathbf{V}_B(\theta,\omega)$ amplifies existing orientation errors in response to motion.

4.5 Separate-bias Kalman filter formulation

The linear error propagation model of (17) provides the basis for a complimentary Kalman filter to estimate these errors. The model has been manipulated into a form in which the gyro biases are assumed constant, thus permitting the direct application of Friedland's separate-bias Kalman filtering results [21]. If the constant-bias model turns out to fit the gyro performance poorly, the restriction can later be ameliorated by use of an age-weighting factor. If an exponential gyro warm-up model as in [15] seems more appropriate, this can be accommodated within Friedland's formulation by replacing the identity submatrix in the state transition matrix of (17).

Switching to Friedland's notation, define an error state vector $\mathbf{x}_k \equiv \delta\theta(t_k)$ and a bias state vector $\mathbf{b}_k \equiv \delta\omega(t_k)$ where t_k is the time at the k[th] iteration of the algorithm. An augmented state vector $\mathbf{z}_k \equiv [\mathbf{x}_k \quad \mathbf{b}_k]^T$ satisfies

$$\mathbf{z}_{k+1} = \mathbf{F}_k \mathbf{z}_k + \begin{bmatrix} \mathbf{I} \\ 0 \end{bmatrix} \mathbf{w}_k$$
$$\mathbf{F}_k = \begin{bmatrix} \mathbf{A}_k & \mathbf{B}_k \\ 0 & \mathbf{I} \end{bmatrix} \tag{19}$$

The additive white noise $\mathbf{w}_k$, with variance $\mathbf{Q}_k$, only effects $\mathbf{x}$, since $\mathbf{b}$ is assumed constant. The measurement equation is

$$\mathbf{y}_k = \mathbf{L}_k \mathbf{z}_k + \mathbf{v}_k \,. \tag{20}$$

where $\mathbf{v}_k$ is white noise with variance $\mathbf{Q}_k$. In Friedland's paper, $\mathbf{L}_k = [\mathbf{H}_k \;\; \mathbf{C}_k]$, but in this application the measurements from the inclinometers and compass only measure $\mathbf{x}$ and not $\mathbf{b}$, so $\mathbf{C} = 0$ will be used throughout, resulting in a great simplification from Friedland's derivation.

Applying Kalman filtering to this model, the optimal estimate of $\mathbf{z}$ is

$$\hat{\mathbf{z}}_{k+1} = \mathbf{F}_k \hat{\mathbf{z}}_k + \mathbf{K}(k+1)(\mathbf{y}_{k+1} - \mathbf{L}\mathbf{F}_k \hat{\mathbf{z}}_k) \tag{21}$$
$$\mathbf{K}(k) = \mathbf{P}(k)\mathbf{L}^T\left[\mathbf{L}\mathbf{P}(k)\mathbf{L}^T + \mathbf{R}_k\right]^{-1} . \tag{22}$$

The Ricatti equations for the recursive computation of the estimation error covariance matrix $\mathbf{P}(k)$ needed in the Kalman gain expression can be rolled together into the single predictor-to-predictor covariance update equation:

$$\mathbf{P}(k+1) = \mathbf{F}_k[\mathbf{I} - \mathbf{K}(k)\mathbf{L}]\mathbf{P}(k)\mathbf{F}_k^T + \begin{bmatrix} \mathbf{I} \\ 0 \end{bmatrix} \mathbf{Q}_{k+1}[\mathbf{I} \;\; 0] \tag{23}$$

Partitioning $\mathbf{P}(k)$ into 3-by-3 submatrices as

$$\mathbf{P}(k) = \begin{bmatrix} \mathbf{P}_x(k) & \mathbf{P}_{xb}(k) \\ \mathbf{P}_{xb}^T(k) & \mathbf{P}_b(k) \end{bmatrix}, \tag{24}$$

the expression for the Kalman gain, (22), may be rewritten in partitioned form as

$$\begin{bmatrix} \mathbf{K}_x(k) \\ \mathbf{K}_b(k) \end{bmatrix} = \begin{bmatrix} \mathbf{P}_x(k)\mathbf{H}^T\left[\mathbf{H}\mathbf{P}_x(k)\mathbf{H}^T + \mathbf{R}_k\right]^{-1} \\ \mathbf{P}_{xb}^T(k)\mathbf{H}^T\left[\mathbf{H}\mathbf{P}_x(k)\mathbf{H}^T + \mathbf{R}_k\right]^{-1} \end{bmatrix} . \tag{25}$$

These separate gains are used in two essentially separate Kalman filters, one for estimating $\mathbf{x}$ and one for $\mathbf{b}$. To compute the $\mathbf{K}_x$ and $\mathbf{K}_b$ gains in (25), covariance submatrices $\mathbf{P}_x$ and $\mathbf{P}_{xb}$ are needed. These are updated by the partitioned version of (23):

$$\begin{aligned}
\begin{bmatrix} \mathbf{P}_x^{+} & \mathbf{P}_{xb}^{+} \\ \mathbf{P}_{xb}^{T+} & \mathbf{P}_b^{+} \end{bmatrix} &= \begin{bmatrix} \mathbf{A}_k & \mathbf{B}_k \\ 0 & \mathbf{I} \end{bmatrix} \left(\begin{bmatrix} \mathbf{I} & 0 \\ 0 & \mathbf{I} \end{bmatrix} - \begin{bmatrix} \mathbf{K}_x \\ \mathbf{K}_b \end{bmatrix} [\mathbf{H} \;\; 0] \right) \times \\
&\quad \begin{bmatrix} \mathbf{P}_x & \mathbf{P}_{xb} \\ \mathbf{P}_{xb}^T & \mathbf{P}_b \end{bmatrix} \begin{bmatrix} \mathbf{A}_k & \mathbf{B}_k \\ 0 & \mathbf{I} \end{bmatrix} + \begin{bmatrix} \mathbf{Q}_k & 0 \\ 0 & 0 \end{bmatrix} \\
&= \begin{bmatrix} \mathbf{A}_k - \mathbf{A}_k\mathbf{K}_x\mathbf{H} - \mathbf{B}_k\mathbf{K}_b\mathbf{H} & \mathbf{B}_k \\ -\mathbf{K}_b\mathbf{H} & \mathbf{I} \end{bmatrix} \times \\
&\quad \begin{bmatrix} \mathbf{P}_x\mathbf{A}_k^T + \mathbf{P}_{xb}\mathbf{B}_k^T & \mathbf{P}_{xb} \\ \mathbf{P}_{xb}^T\mathbf{A}_k^T + \mathbf{P}_b\mathbf{B}_k^T & \mathbf{P}_b \end{bmatrix} + \begin{bmatrix} \mathbf{Q}_k & 0 \\ 0 & 0 \end{bmatrix}
\end{aligned} \tag{26}$$

Thus, a plethora of 6-by-6 matrix multiplications and one 6-by-6 inversion are replaced by a somewhat greater number of 3-by-3 multiplications and one 3-by-3 inversion.

5. Implementation

Figure 4 illustrates the configuration of the hardware built to demonstrate the inertial head-attitude tracking concept. The sensors are all embedded in a specially machined 2" X 2" X 1.25" plastic block connected by a thin 10' cable to an analog signal conditioning circuit and data acquisition card in a PC.

Software was written in "C" to run on the PC and implement the basic loop shown in Figure 5.

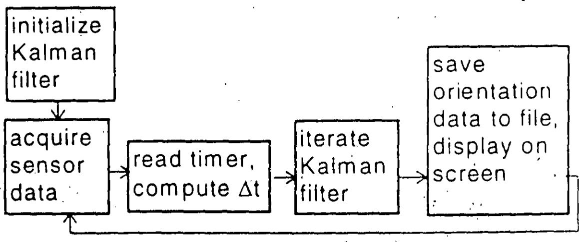

Figure 5: Inertial orientation tracker main software loop.

The initialization block, executed once at program start-up, sets the initial state estimates and covariances as follows:

$\mathbf{x}_0$: The inclinometer is read and used to set ψ and θ. The compass, if used, determines ϕ; otherwise ϕ=0.

$\mathbf{b}_0$: The biases of all 3 gyros are measured during system calibration and stored in a file. On initialization, the file is read and $\delta\omega$ is initialized with the stored gyro biases.

$\mathbf{P}_x(0)$: The errors in the initial determination of the Euler angles may be substantial, but they are assumed to be uncorrelated with one another: $\mathbf{P}_x(0) = \mathbf{I}$.

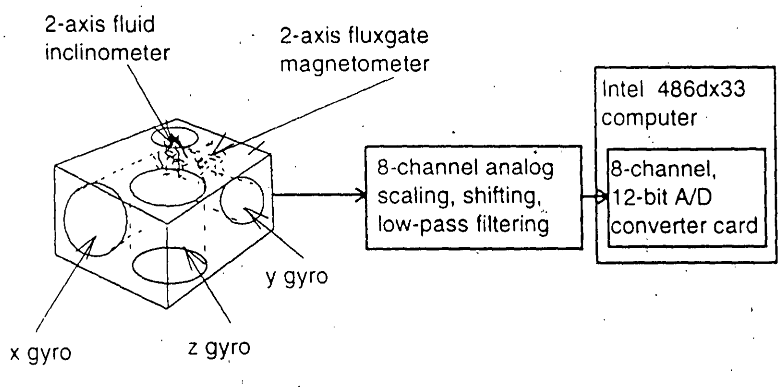

Figure 4: Orientation tracker hardware configuration.

$P_b(0)$: The gyro biases at start-up could differ substantially from the prerecorded calibration values, but the uncertainties are uncorrelated: $\mathbf{P}_b(0) = 0.1\mathbf{I}$.

$P_{xb}(0)$: The initial uncertainties in orientation and gyro bias are completely uncorrelated: $\mathbf{P}_{xb}(0) = \mathbf{0}$.

The data acquisition block scans all the A/D channels in rapid succession. The new gyro readings are stored as $\omega(t+\Delta t)$ and the previous ones are moved back to $\omega(t)$. The new inclinometer and compass readings are stored in $y(t+\Delta t)$. In the next block, a timestamp is obtained from the 8253 timer/counter chip on the PC motherboard. This counter is driven by a 1.19 MHz oscillator with a 65,536 divisor to generate 18.2 Hz timer ticks for BIOS and DOS time-keeping. By reprogramming the divisor it was found possible to obtain sub-microsecond timing resolution as required for inertial integration. Δt is calculated as the difference between the current timestamp and the previous one.

Next, $\omega(t)$, $\omega(t+\Delta t)$ and Δt are fed into the Kalman filter update block. $\mathbf{W}_B$ and $\mathbf{V}_B$ are computed and then used in (14) to compute the predicted $\theta(t+\Delta t)$. This corresponds to the attitude computation block in. Since the Euler angle estimates, $\hat{\theta}$ must be maintained anyway, it is convenient to subsume $\delta\hat{\theta}$ into them, and keep track of total estimates only. This does not change the filter framework developed in the previous section in any important way; it just means that $\delta\hat{\theta}(t)$ is always zero at the beginning of each iteration of the Kalman filter. At the end of the Kalman filter update cycle, $\delta\hat{\theta}(t+\Delta t)$ is used to reset $\hat{\theta}(t+\Delta t)$ and then flushed back to zero before the next cycle. Since the attitude error estimates are propagated along with the attitude estimates through the nonlinear propagation equation, the top three elements of $\mathbf{F}_k\hat{\mathbf{z}}_k$ in (21) are replaced with zeros. Since ω is *not* included in the state, the running estimates of $\delta\hat{\omega}$ must still be kept track of in the Kalman filter. They are propagated through the prediction step unchanged, as governed by the bottom three rows of $\mathbf{F}_k$. The system, then , can be thought of as a mixture of a purely complimentary Kalman filter as described in the previous section and an extended Kalman filter which keeps track of total estimates of state.

The next stage in the computational loop is to incorporate the measurements and update the error estimates as follows

$$\begin{aligned}\delta\hat{\theta}_{k+1} &= \delta\hat{\theta}_{k+1} + \mathbf{K}_x(k+1)\mathbf{v}_{k+1} \\ \delta\hat{\omega}_{k+1} &= \delta\hat{\omega}_{k+1} + \mathbf{K}_b(k+1)\mathbf{v}_{k+1}\end{aligned} \tag{27}$$

where $\mathbf{v}_{k+1}$ is the innovations obtained by subtracting the predicted orientation estimates from the new orientation measurements. In order to calculate $\mathbf{K}_x(k+1)$ and $\mathbf{K}_b(k+1)$ with equation (25) it is necessary to first propagate the covariance submatrices using (26). Since the inclinometer and compass signals are pre-processed to give direct measurements of the Euler angles, $\mathbf{H}=\mathbf{I}$, and (26) is simplified to the following steps:

$$\begin{aligned}\mathbf{T}_1 &= \mathbf{A} - \mathbf{A}\mathbf{K}_x \\ \mathbf{T}_2 &= \mathbf{T}_1\mathbf{P}_{xb} \\ \mathbf{T}_3 &= \mathbf{B}\mathbf{T}_2^T \\ \mathbf{P}_b^+ &= \mathbf{T}_2 + \mathbf{B}\mathbf{P}_b \\ \mathbf{P}_{xb}^+ &= \mathbf{T}_2 + \mathbf{B}\mathbf{P}_b^+ \\ \mathbf{P}_x^+ &= \mathbf{P}_{xb}^+\mathbf{B}^T + \mathbf{T}_3 + \mathbf{T}_1\mathbf{P}_x\mathbf{A}^T\end{aligned} \tag{28}$$

where $\mathbf{T}_i$ are simply temporary storage matrices used to reduce the amount of redundant matrix multiplication. A small subroutine library was written, following the pointer conventions and numerical methods described in [22], to perform the necessary matrix multiplication, transposition, addition and inversion operations to carry out these steps.

5.1 The Q_k and R_k Matrices

Ideally, Q_k is supposed to reflect the magnitude of a white noise sequence. If all error sources in the inertial attitude system are taken care of (i.e. modeled in the state propagation matrix), then $\mathbf{w}_k$ in (19) should be entirely due to the noise floors of the angular rate sensors. In this case, it should be possible to calculate the optimal value of Q_k by measuring the noise covariance, $\mathbf{Q}$, of the stationary gyros in advance, then at each time step compute $\mathbf{Q}_k = \mathbf{G}_k\mathbf{Q}\mathbf{G}_k^T$, using $\mathbf{G}_k = \mathbf{W}_B(\theta(t_k))$.

However, there are many nonwhite error sources besides bias, such as nonlinearity, hysteresis, misalignment, g-sensitivity, and scale factor temperature coefficient, none of which are modeled in the current implementation. The best procedure for designing a reduced-order Kalman filter under these circumstances is to use a Schmidt-Kalman filter, which eliminates the unmodeled states from the state vector, but continues to propagate their covariances in partitioned Ricatti equations and $\mathbf{Q}$ and $\mathbf{R}$ matrices. A simpler approach, which sometimes works almost as well [12, p. 397], is to just ignore the unmodeled states, but "bump up" the $\mathbf{Q}$ and $\mathbf{R}$ matrices to account for the noises in the states being discarded. This approach is taken here, except the "bumping up" is done in a very inexact way.

Without having a model of the gyro dynamics, the following error sources in the process equation (19) are assumed:

gyro noise: From an oscilloscope, for stationary gyros, σ=0.01 rad/s. Covariance per step $(0.01\Delta t)^2$.

integration rule error: From the analysis in Section 4.3, $\sigma \approx \omega^3\Delta t^2$ rad/s. Covariance per step $\omega^6\Delta t^6$.

scale factor error: This is a composite of nonlinearity and temperature dependent scale factor variations. Assuming scale factor accuracy of 1% of full scale, $\sigma \approx 0.01\omega$ rad/s. Covariance per step $(0.01\omega\Delta t)^2$.

Assuming Δt=0.01sec, and that these error sources are uncorrelated, the error covariances add up to approximately $10^{-8}(1+\omega^2+10^{-4}\omega^6)$. At each iteration of the Kalman filter software, the following algorithm is used to compute $\mathbf{Q}_k$:

1. find $\omega_{max} = \max(\omega_x, \omega_y, \omega_z)$
2. set $\sigma_w^2 = 10^{-8}(1+\omega_{max}^2+10^{-4}\omega_{max}^6)$
3. set $\tilde{Q}_k = \begin{bmatrix} \sigma_w^2 & 0 & 0 \\ 0 & \sigma_w^2 & 0 \\ 0 & 0 & \sigma_w^2 \end{bmatrix}$
4. set $Q_k = W_B \tilde{Q}_k W_B^T$

This algorithm is very crude and likely to overestimate Q_k because it uses ω_{max} to find the variance for all three diagonal elements of $\mathbf{Q}_k$.

$\mathbf{R}_k$ is modeled in an equally sloppy manner. The measurement noise is extremely nonwhite. The major source of measurement noise for the fluid inclinometers is "slosh" caused by transverse linear accelerations. Linear motion is not included in the state vector, and therefore, this error cannot be modeled in the measurement matrix. Furthermore, the magnitude of the low-frequency "slosh" errors are sometimes extremely large: up to 1 radian. Slosh-induced inclination errors cause similarly large heading errors in the compass system. On the other hand, when the head is still, there is no slosh and the attitude angles measured by the inclinometer are very accurate. The algorithm for $\mathbf{R}_k$ is therefore designed in a heuristic way to force the Kalman filter to take good advantage of the measurements when they are likely to be meaningful, and to ignore them when they are likely to be erroneous. The basic principle is that σ_v should approach 1 when slosh is likely, and approach the static accuracy of the inclinometer/compass measurements, about 0.01 radians, when slosh is very unlikely. In the absence of a model for human head motion, it is assumed that a person cannot sustain a constant linear acceleration of the head very long with no rotation. Therefore, the longer the period of time that the head has had 1) zero angular velocity, and 2) unchanging inclinometer outputs, the higher the probability that the head is still. Based on this intuition, the algorithm used to set $\mathbf{R}_k$ is:

1. compute "stilltime", τ, since last non-zero gyro reading OR last change in inclinometer reading.
2. set $\sigma_v = 1/(1+400\tau)$
3. if $\sigma_v < 0.01$, set $\sigma_v = 0.01$
4. set $\mathbf{R}_k = \begin{bmatrix} \sigma_v^2 & 0 & 0 \\ 0 & \sigma_v^2 & 0 \\ 0 & 0 & \sigma_v \end{bmatrix}$.

According to this algorithm, the measurement error covariances for the inclinometer roll and pitch range from 1, during periods of likely slosh, down to 10^{-4}, during periods of likely stillness. The covariance of the compass yaw error only comes down to 0.01, corresponding to $\sigma \approx 6°$, because even with good inclinometer information, magnetic distortions in the room make the compass this inaccurate.

6. Results

Using the $\mathbf{Q}_k$ and $\mathbf{R}_k$ matrices described above, it was found that the Kalman filter diverged within a few seconds when the sensor was still. An age weighting multiplier did not help. After much experimentation, it was found that the only way to prevent divergence is to never let the diagonal elements of $\mathbf{R}_k$ be less than 1. The algorithm for $\mathbf{R}_k$ was adjusted so that σ_ω ranges from 10, when τ=0, to 1, when τ>0.2. The base level of $\mathbf{Q}_k$ was also boosted from 10^{-8} to 10^{-4} so that the filter would still make use of the measurements with the larger measurement noise covariance. With these modifications, the filter remains stable indefinitely and succeeds in eliminating long term drift without compromising the rapid dynamic response of the inertial tracking technique. The filter can run at approximately 200 iterations/second. This is a five-fold slowdown as compared to the raw attitude computation with the Kalman filtering steps commented out. However, it is still reasonably fast and the delay can be compensated for by prediction if necessary.

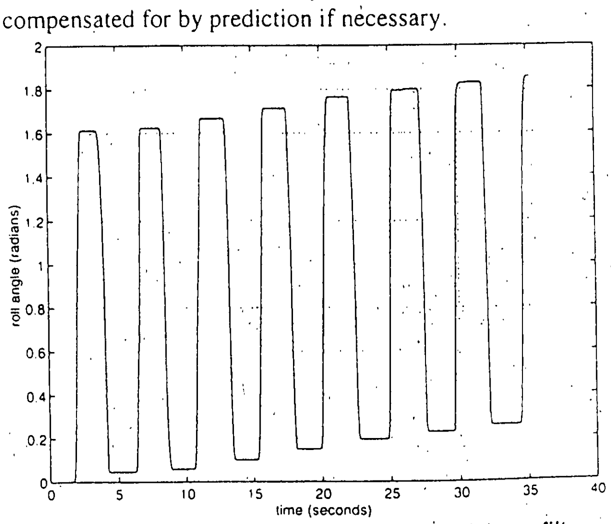

Figure 6: Test run without complimentary Kalman filter.

To demonstrate the behavior of the filter, two datasets were collected. In the first dataset, the complimentary

Kalman filter block is disabled by setting $\mathbf{K}_x$ and $\mathbf{K}_b$ equal to zero. During the test period of approximately 35 seconds, the sensor block was repeatedly turned through +90° about the roll axis and left to rest on its right side, then returned to rest in its horizontal orientation on the table. The roll Euler angle is plotted against time in Figure 6, which demonstrates the problem with unaided inertial integration: the accumulated drift error by the end of the run is about 15°. The second dataset is created by a similar motion sequence, but the Kalman filter is in effect. As Figure 7 shows, the filter incorporates the drift-free but noisy measurements from the inclinometers, and effectively compensates the drift of the inertial system. Due to the time-varying $\mathbf{R}_k$ strategy which shuts out the measurements during motion, a certain amount of error accumulates each time the sensor is rolled over and back, and the Kalman filter corrects it once the sensor returns to a stationary pose. The graph clearly shows the time-course of this corrective action.

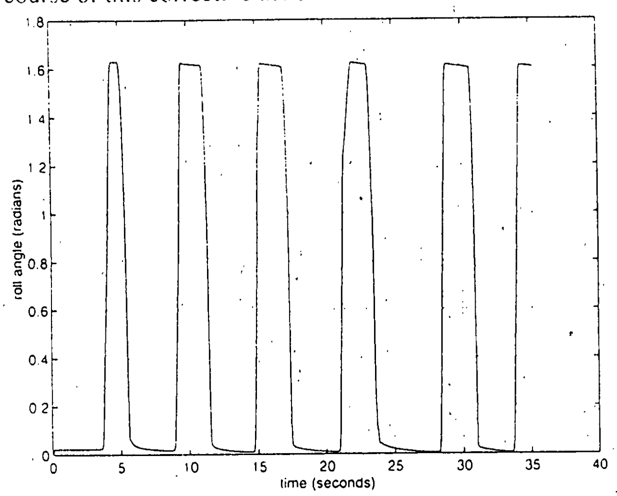

Figure 7: Test run with complimentary Kalman filter.

7. Acknowledgements

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TECHNOLOGY REVIEW

January/February
VR DEVELOPMENT SOFTWARE

March
3D NAVIGATIONAL & GESTURAL DEVICES

April
SOURCELESS TRACKERS

HEAD-MOUNTED DISPLAYS

3D ACCELERATORS

FORCE-FEEDBACK TECHNOLOGY

August/September
CAVE's

October
HUMANOIDS

November
MOTION PLATFORMS AND SYSTEMS

December
3D OBJECT AND TERRAIN LIBRARIES

Sourceless Trackers

Robin Hollands

Much of the most advanced technology for 'sourceless' trackers has been developed for use in inertial guidance systems for missiles and other military hardware, and is unlikely to be commercially available in the near future. The VR marketplace, which could consume in the future very large numbers of low-cost, high-performance sourceless trackers, will just have to rely on commercial and academic R&D. In this article, Robin Hollands provides a status report, a beginner's guide to some of the technologies of sourceless trackers, and a list of useful contacts.

Most forms of tracker system used in virtual reality applications introduce restrictions because of the need for a source. Whether the technology used is mechanical, ultrasonic or electromagnetic, all require some form of base station from which to assess position and orientation. This requirement leads to a number of possible problems: operating range limitations, line-of-sight obstruction, etc. Sourceless trackers on the other hand are by definition tracking systems that do not require a base, or source, and these problems do not therefore arise. In theory, a sourceless tracker could operate in any environment and over an unlimited operating range, surely making it the ideal solution for almost any VR application.

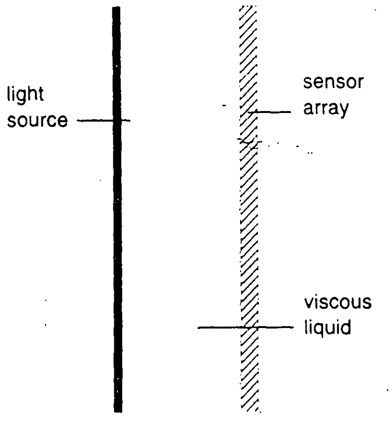
However, despite the obvious desirability of such a device, a survey of the field reveals a surprising lack of research activity, either commercial or academic. The only full time researcher found was Eric Foxlin, at MIT, and I am indebted to him for much of the information in this article.

For full six degrees of freedom tracking, both orientation and linear position need to be determined. There are a number of technologies and methods that can be used to assess either or both of these, of which the following will be considered in this review: – inclinometer, compass, gyroscope, accelerometer, and optical flow.

Inclinometers

Inclinometers, or tilt sensors, measure the tilt of an object with respect to gravity. Although this makes them not truly sourceless (since the mass of the earth is their source), operating range is effectively infinite and interference negligible. In essence, an inclinometer is purely

> ***"However, despite the obvious desirability [of sourceless trackers], a survey of the field reveals a surprising lack of research activity, either commercial or academic"***



A form of inclinometer patented by Texas Instruments, designed for use with virtual reality headsets and other peripherals. A confined tube containing a viscous liquid has a light source on one side, and a photosensor array on the other. By analysing the output of the sensor array the angle of tilt can be determined.

an instrumented pendulum. A simple inclinometer can be homebrewed by hanging a weight from two perpendicular potentiometers. Commercial 2-axis inclinometers consist of a small glass bubble, half-filled with an electrolytic fluid, and containing five electrodes. As the sensor is tilted, the level of the fluid on each electrode changes, which can be sensed by the driving electronics and converted into pitch and roll values.

Although it is typically used for measuring tilt with respect to gravity, it should be noted that what the inclinometer is actually measuring is the direction of total acceleration. If the sensor is stationary with respect to the room, then all of the acceleration is caused by gravity and the tilt sensor gives a correct reading. However, if the tilt sensor is attached to a moving head, the inclinometer will also be affected by the acceleration of the head moving around, resulting in an incorrect reading of tilt. This combined with the settling time of the fluid within the sensor can lead to the virtual world 'sloshing around' for rapid movements. Electrolytic inclinometers also have a finite rotational operating range, determined by the angle at which the electrodes become dry.

Tilt switches

It should be noted that tilt sensors are different from tilt switches. Tilt sensors provide an analogue measure of tilt over their operating range. Tilt switches typically consist of a small quantity of mercury in a miniature container with two contacts in its base. When the tilt switch is upright, the mercury closes the circuit between the two contacts. When the switch is tilted, the mercury rolls off the contacts opening the circuit. Tilt switches can detect only whether the tilt angle is greater or less than their activation angle, but not what the value of the tilt is. Multiple tilt switches, each at a slightly different angle, can be multiplexed to provide a pseudo-continuous reading of angle, but are usually incorporated into low-cost flying joysticks to provide simple left/right back/forward controls.

Although inclinometers can be very good at providing a reading of any rotation relative to the vertical, rotations in a horizontal plane, or heading, will not affect a pendulum device and require a different sensing technology. Luckily nature provided a second 'source' for sourceless trackers to use - the earth's magnetic field.

Compasses

The earth is effectively a giant bar magnet with the magnetic north pole near the physical north pole and a magnetic field running from north to south. Although this rarely runs parallel with the surface of the earth, in most places it has a horizontal component that can be sensed for heading purposes. Simple compasses contain a low friction surface supporting a magnetised bar which aligns itself with the local magnetic field.

Hall effect semiconductors

Although these have been used via servos to electronically measure heading, most miniature electronic compasses now use

GRAVIMETRIC TRACKERS	Accuracy Heading	Accuracy Tilt	Resolution Heading	Resolution Tilt	Repeatability Heading	Repeatability Tilt	Range Heading	Range Tilt	Update Rate
General Reality									
CyberTrak	±0.5°	±0.2°	0.1°	0.2°	±0.1°	0.2°	360°	±25°	8Hz
VictorMaxx Technologies									
Cybermaxx tracker	±5°-±3°	±1°	±0.1°	±0.1°	0.1°	0.1°	360°	±45°	30Hz-8Hz

Hall effect semiconductors. Hall effect compasses use Fleming's left hand rule. In motors, a current flowing in a magnetic field results in a motion in a plane perpendicular to the two, spinning the rotor. If the current is flowing through a semiconductor device in a magnetic field, the resulting motion takes the form of the electrons moving ~~to one~~ side. This results in a higher concentration of electrons on one side of the semiconductor than the other, which can be measured as an e.m.f. across the slice.

When used as a compass, an individual hall effect sensor will report the component of the earth's magnetic field aligned with it. This can lead to ambiguities between say, NE and NW, and therefore another perpendicular Hall effect sensor is used. The two readings can be combined using trigonometry to find the local magnetic north.

Calibration

Electronic compasses suffer from two main problems. The first is that the dip and direction of the earth's magnetic field varies according to location, resulting in a need to calibrate the unit in its local area. The second problem is analogous to that which affects electromagnetic trackers, namely that the earth's magnetic field is subject to interference from ferrous metal in the environment, e.g. furniture, wall reinforcements, head mounted displays etc. Researcher Eric Foxlin has found that this can cause variations in magnetic north of ± 30 degrees within a few feet.

Gravimetric sensors

Electronic compasses are usually combined with an inclinometer (producing what is sometimes referred to as a 'gravimetric' sensor) to provide a full 3DOF orientation system, the quality of which can vary – see comparison table at foot of page opposite.

Gyroscopes

The most common type of gyroscope is the spinning wheel type, similar to those found in toy shops. A relatively heavy wheel is spun freely suspended in a supporting frame. The spinning mass has a large rotational inertia resisting rotation away from its plane. This has the effect that the gyroscope continues to point in the same direction, regardless of the orientation or movement of the base the frame is mounted on. Instrumenting the gimbals on the supporting frame can therefore provide a two degree of freedom indication of orientation. Another gyroscope oriented perpendicularly to the first is required to give a full three degree of freedom orientation measurement.

Because gyroscopes rely purely on inertia, they are genuinely sourceless, and will even work in space, dependant neither on gravity nor any magnetic field. This does however give rise to a problem. Simplistically, a gyroscopic pointed at the sun will stay pointed at the sun, regardless of the motion and rotation of the earth. This leads to apparent rotation and dipping of the orientation of the gyroscope when viewed on the earth.

For this reason a normal gyroscope is not appropriate for use as a compass; however the addition of a weight on the inner gimbal ring on the gyroscope assembly results in eccentricity in its motion. This causes the gyro gradually to align itself with the third 'source' that nature has put in place for sourceless trackers – the rotation of the earth. This in turn causes the axis of the gyroscope to swing round until it points north, and this can provide a much more accurate compass than any magnetic system.

Rate gyroscopes

Gyroscopes only continue pointing in the same direction in a theoretically ideal system. In the real world it is hard to achieve frictionless gimbals in the gyroscope assembly, and any friction causes a drift in the readings. Many gyroscopes are not of the position variety, reporting the absolute angle of the gyroscope wheel, but of the rate gyroscope variety, reporting the rate of change of the gyroscope angles. To get position information from these, the rate must be integrated. Any error in the rate readings will cause an extra term in the integration, which reveals itself as further drift. This is typically in the order of 1 degree per minute, i.e. if the user stands perfectly still, the virtual world will rotate 60 degrees in an hour.

GYROSCOPIC TRACKERS	Accuracy Yaw	Accuracy Pitch & Roll	Resolution Yaw	Resolution Pitch & Roll	Range Yaw	Range Pitch & Roll	Update Rate
VR Systems UK GyroTRAC	15°/min drift (max)		0.003° — 0.032°		±6° — ±66°		50Hz
Angularis Inertial Tech. Prototype	~3°/min drift	1°	0.0082°	0.0082°	±180°	±90°	1KHz

Although this rate of drift would not be immediately noticeable in an opaque head mounted display, the cumulative effect in tilt or roll will eventually become obvious and must be compensated for in a useable system, usually by measuring the drift on a stationary object for an extended period of time, and then using this as a compensating factor. The problems mentioned before with the earth's rotation can be compensated for similarly.

Gyroscopic trackers used for manipulation purposes often have a clutch button that only reads data from the tracker when a movement is desired to be recorded. Because all movements are therefore relative, drift is not a significant problem.

Coriolis effect

Rate gyros also come in solid state form, and use the Coriolis effect, named after the French engineer and mathematician who first drew attention to it (and who also wrote a treatise on the mathematics of the game of billiards). The Coriolis force is experienced by anything moving on a rotating body, and is exerted perpendicular to both the axis of rotation and the direction of the velocity. A simple experiment is to stand on the outside of a child's merry-go-round facing the centre while it is spinning, and then try to kick the axis; the Coriolis force will cause your foot to go to one side.

The same principle is used in Murata's piezoelectric gyroscope which consists of a triangular prism, with an exciter on one face and receivers on the other two. The exciter sends out pulses (kicks) at the prism's resonant frequency, which are picked up equally by both detectors. Any rotation around the axis of the prism produces a Coriolis force, which causes the amplitude of the received signal to be greater at one detector than the other. The rate of rotation can then be measured as a proportion of the difference between the two detector readings.

Systron-Donner's rotation sensor operates in a similar way with a piezoelectric tuning fork type device whose prongs oscillate in a single plane. The application of a rotation causes a Coriolis force making the prongs also oscillate in a perpendicular plane with an amplitude proportional to the rate of rotation.

It appears that the only gyroscopic headtracker available off the shelf is that offered by VR Systems UK, although Willow Technologies have announced the prototype of a rate reporting gyroscopic tracker, and Eric Foxlin's start-up company Angularis Intertial Technologies also has an orientation tracker in the prototype stage.

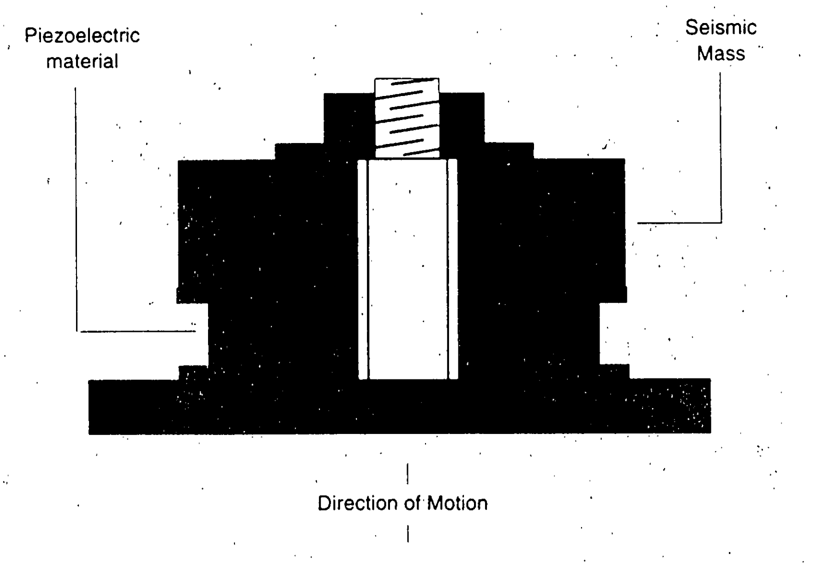
Although gyroscopes or inclinometer/compass trackers can measure orientation well, both have the disadvantage of not being able to measure location in space. One possible solution to this is to use accelerometers.

Accelerometers

Accelerometers are simply devices that measure acceleration in a given direction. Most use Newton's second law, i.e. Force=mass*acceleration. This is often measured by a mass attached to piezoelectric material. Any acceleration causes the mass to exert a force on the piezoelectric material which generates an e.m.f. in response. Accelerometers can also be based around spring masses moving along a linear potentiometer, or in a capacitor or inductor.

To get position data from the acceleration data is simply a matter of integrating the result twice. However, in the same way as a single integration caused rate gyroscope errors to appear as drift, the double integration causes any accelerometer errors to grow quadratically

Piezoelectric Accelerometer



with time. There is also a problem with gravity, which is also an acceleration. A stationary accelerometer pointing straight down will read an acceleration of 9.81ms-2, and any accelerometer not exactly perpendicular to gravity will always exhibit some component. Remember that any errors measuring the real acceleration show as quadratically increasing errors when integrated to position! It is for this reason that accelerometers cannot be used in isolation, but must be used with an accurate inclinometer.

Although miniature low-cost accelerometers are available, these have been developed for the automotive industry for use in crash bags and measure accelerations of around 50g. Typical human head accelerations rarely exceed 2g and are usually out of the usuable range of these devices.

Because of all the problems involved with accelerometers, it is perhaps no surprise that no companies were found that have a successful accelerometer-based position tracker, although one is under development by Angularis Inertial Techologies

Optical flow

Apparently still only a theoretical system at present, optical flow uses a set of cameras mounted on the tracker to process the optical flow of an unstructured environment around it. In simple terms, this involves using real-time image processing to extract features from the environment, measuring apparent position changes of the features as the user moves around, and continuously computing the user's position relative to the features.

For more information see Bishops G. and Fuchs H., "A self-tracker: a smart optical sensor on silicon" in Proc. 1984 Conference on Advanced Research on VLSI.

Conclusions

There are undoubtedly problems and deficiencies with currently available sourceless tracking systems and technologies. Although these may eventually become insignificant over time with the development of better sensors, the answer may well lie in hybrids of different sourceless technologies, used perhaps in combination with sourced tracking. For example, compass/inclinometer systems can produce very accurate results for a stationary body, gyroscopes are accurate for a short time but suffer from drift.

A possible solution being developed by Angularis Intertial Technologies is to use the compass/inclinometer system to automatically recalibrate the gyroscopic system in 'quiet' moments. In a similar fashion, ultrasonic trackers could be used to recalibrate the much faster but error-prone accelerometer based position trackers. Even global technologies such as the satellite GPS (Global Positioning System) could be called upon for large scale systems.

Sourceless trackers, used in combination with wireless signal transmission and portable workstations and battery packs, offer the prospect of virtual world navigation free from the shackles of a base station. Although the desirability of a HMD-blinded user stumbling around without restraint may be questioned, free ranging use will certainly be necessary for many of the augmented reality applications to come. Exponents of sourceless tracking also point out that the removal of a requirement for signal transmission and reception, and the specialised signal processing hardware found in many sourced trackers, should produce exceptionally cheap units. Truly sourceless technologies, such as inertial systems, are also immune from the interference that plagues current users of electromagnetic and ultrasonic tracking systems. In the end, it may well purely be the convenience of sourceless tracking that makes it the system of the future.

Contact List

The list which follows on pages 28 and 29 has been divided into two colour-coded sections. The first section comprises organisations who manufacture, or are planning to manufacture sourceless tracking systems. In this context a system is defined as a sensing unit that is ready for computer connection, i.e. plug-and-play. The second section lists a selection of vendors of sensor components, for the benefit of organisations and researchers thinking of developing a sensor system. Note that the basic sensors used in sourceless devices are also found in numerous other applications. The list of sensor suppliers is limited to vendors known to provide sensors for existing VR systems, or whose existence has been brought to our attention by those working in the field.

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Tracking Position and Orientation in a Large Volume

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ABSTRACT

Tracking position and orientation accurately and precisely is important in building effective virtual reality systems. Commercially available trackers perform six-degrees-of-freedom tracking adequately but only over limited volumes. Large volume trackers are not available commercially, yet they are necessary to build effective augmented reality[1] systems. This paper presents a new approach to large-volume six-degree-of-freedom tracking. Our approach uses ultrasonic measurement technology and cellular deployment to achieve a relatively low-cost large-volume tracker.

INTRODUCTION

An augmented reality (AR) system [Caudell and Mizell 92] augments a user's view of his surroundings with pictorial, textual, or both kinds of information. AR systems seem very promising for use in simplifying tasks requiring touch labor, especially manufacturing, assembly, and repair tasks. One possible application of AR being studied at Boeing uses pictorial information to help assembly workers build wire bundles more rapidly and accurately. The AR system effectively "draws" the placement of wires on a formboard[2] by successively drawing each wire's path on a worker's AR display. The worker sees the wire path as if it were resting on the surface of the formboard. The assembly worker removes the appropriate wire from that wire-bundle's assembly kit and attaches that wire to the formboard along the path drawn by the AR system.

Commercially available tracking systems are not adequate for use in most AR applications because workers seldom perform touch labor in a volume that is only five to seven feet across. A long wire bundle may require as many as five adjacent formboards. An AR system capable of supporting such long wire-bundles needs a tracker that operates in a volume at least a three by three by forty feet.

AR systems are not alone in benefiting from large volume tracking. VR applications also benefit. By translating a VR user's movement within a large physical volume into the equivalent movement in the virtual reality, a VR system significantly enhances the illusion of immersion. Gross body movements add qualitatively to the limited kinesthetic feedback produce by moving or rotating the head. While large-volume tracking can enhance the VR experience, it is fundamentally important in AR applications.

Previous Work

The literature documents various methodologies for performing 6DOF tracking including; mechanical [Sutherland 68, Fake Space, Smith 84], magnetic [Ascension, Polhemus], ultrasonic [Logitech], and optical [Antonsson 89, Cook 88, Sorenson 89] approaches. Various surveys [Applewhite 91, Ferrin 91, Meyer *et al.* 92] discuss these tracking technologies in more detail. One approach to large-volume 6DOF tracking is an optical technique successfully demonstrated by the University of North Carolina [Ward 92].

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[1] Augmented reality (AR) is also known as see-through virtual reality.
[2] A formboard is an easle-like structure that hold a wire-bundle during assembly.

0-7803-1363-1/93 $3.00 © 1993 IEEE

The UNC system relies on two-foot-square metal ceiling tiles containing a matrix of light-emitting diodes. The diodes are spaced evenly along a tile's length and width, and are located at a constant depth within the tile. By assembling the tiles into a larger grid, UNC has constructed a large ceiling filled with evenly-spaced light-emitting diodes. The system's user wears a head-mounted display with four lateral-effect "cameras" that "see" a subset of the light-emitting diodes. By appropriately lighting the ceiling and computing which "camera" sees which light emitting diodes, the system can compute the user's position and orientation.

The current UNC ceiling sits 9' above the floor and covers a 10'x12' area. Within this volume, the system can resolve lateral position to within 2mm and rotational orientation to within 0.2 degrees. The system, however, requires a non-trivial superstructure to support the ceiling tiles and the tiles require careful alignment. The four head-mounted, lateral-effect "cameras" are quite heavy and bulky. In general, the UNC tracker does not lend itself to widespread installation since it requires a significant investment to duplicate.

Overview of Our Approach

Ultrasonic technology has a demonstrated cost advantages over other commercially available six-degree-of-freedom (6DOF) tracking technologies. Logitech's ultrasonic system is currently the least expensive commercially available 6DOF tracker.

Our approach uses Logitech's 6DOF ultrasonic tracking technology and cellular deployment to achieve a large-volume 6DOF tracker. Ultrasonic trackers have a constrained operating range, but if we operate multiple trackers in a cellular architecture, we can track over a much larger volume. A cell's ultrasonic transmitter will typically operate only when the detector is within range of that cell's source. By overlapping cells and using simple predictive logic, a computer can switch from cell to cell as the detector moves out of one cell's operating range and into an adjacent cell's operating range.

The Basic Cell

The basic Logitech 6DOF tracker consists of three parts: a source, a detector, and a control unit. The source has three ultrasonic emitters at the vertices of a large plastic triangle. The detector has three microphones at the vertices of a small plastic triangle. The control unit encloses a microprocessor, signal generation hardware, and three cables that respectively connect the control unit to the computer, to the source, and to the detector.

In operation, the control unit starts a timer and sequentially generates an ultrasonic pulse at each emitter. When the pulses reach the detector, the control unit records the time-of-flight information for each source-emitter detector-microphone pair. The control unit then computes the detector's position and orientation by triangulation. In "raw mode," however, the control unit provides the time-of-flight information directly. Raw mode allows users of the ultrasonic tracker to calibrate the source and detector against one another. Such calibration removes variations due to manufacturing and permits the user to write a triangulation algorithm that improves tracker accuracy.

Figure 1 shows a source and a detector. The source's apex emitter lies flat. The base emitters angle upwards 30° from vertical. Each emitter generates a conically shaped ultrasonic field. The unit can track the detector only where the three fields overlap. In addition to the three emitters, the source also contains a microphone mounted just below the triangle's apex and inside the acoustic cones generated by the base emitters. The source-mounted microphone allows the system to compensate for variations in atmospheric conditions. The distance between the base emitters and the apex microphone does not change, but time-of-flight does change with changes in ambient temperature and pressure. The control unit uses the base-emitter to apex-microphone time-of-flight information to translate other time-of-flight measurements into distance.

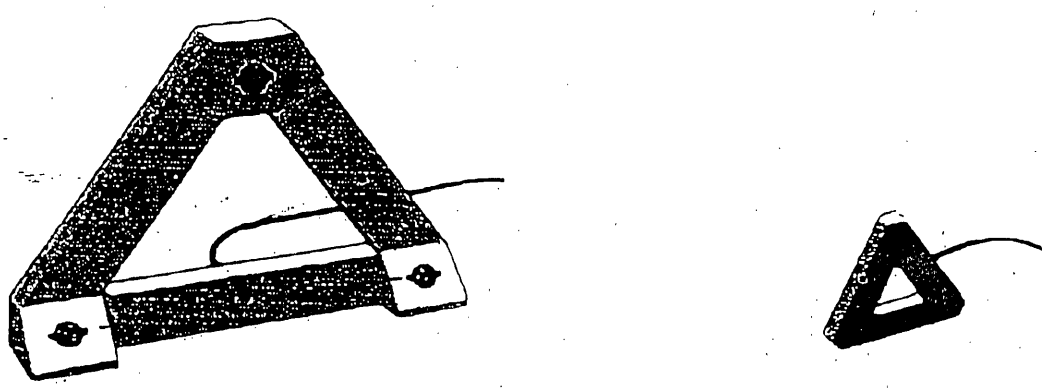

Figure 1. A Logitech source and detector

A cell's geometry and acoustic structure is complex but can be approximated by a truncated cone of constant radius, as shown in Figure 2. The system's tracking region starts approximately six inches below the source and extends four and a half feet further.. The combined acoustic energy of the three emitters spreads out over a 100° field-of-regard. The tracked region's diameter expands by approximately 7 inches for each six inch drop in height. At its base, the cone's tracking radius extends 7 feet 10 inches. By hanging the ultrasonic source seven feet eight inches above the floor, a cell can accommodate individuals 6 foot 6 inch tall and still track a circular region slightly larger than three feet in diameter. In raw mode, a cell's transitional precision is 0.3mm, its accuracy 0.7mm. The rotational precision, 3 feet from the source, is 0.06°, its accuracy 0.15°; at six feet, rotational precision drops to 0.11° and accuracy drops to 0.3°.

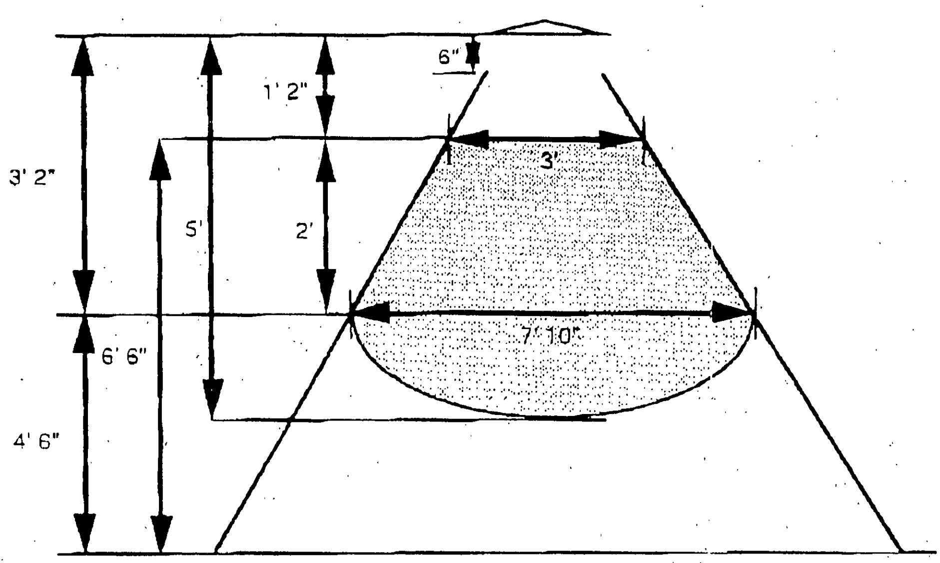

Figure 2. A single cell, its geometry and acoustic structure.

Multiple Cells

Figure 3 shows a profile for a two cell tracker. The geometry is similar to that of the basic cell. Two sources hang nine feet above the ground and three feet apart. Their regions-of-regard touch six feet six inches above the ground and overlap below that level.

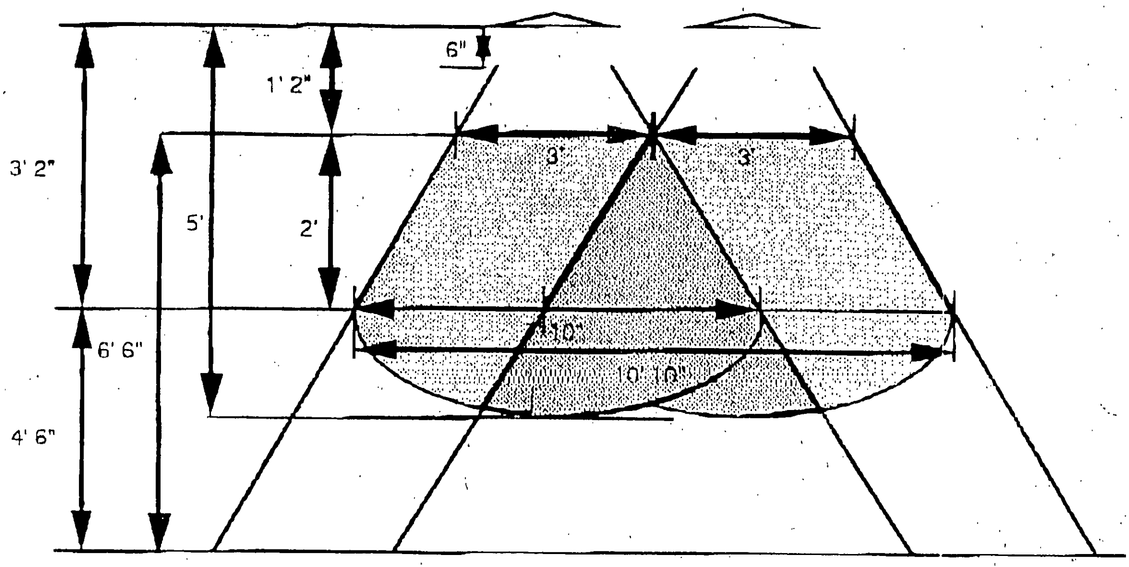

Figure 3. Two cells, their geometry and acoustic structure.

Unfortunately, two adjacent cells cannot operate simultaneously because the cells all emit ultrasonic pulses at the same frequency. Two neighboring cells that operate at the same time will interfere with one another. If we wish to build a cellular tracker, we need to provide a method for selectively activating cells.

We built a switch box that substitutes one source for another under computer control. The switch box plugs into the Logitech controller in place of a source. The sources in turn plug into the switch box. The box contains a set of analog switches ganged together so that they can selectively connect the wires from the Logitech controller to any one source. The prototype switch box can control only two cells, but the technique easily accommodates more.

Volume filling

Figure 4 shows a plan view of various basic cell arrangement that result in large area coverage. If **r** represents a single cell's detection radius then we can cover the greatest volume by separating the sources by a distance of $\frac{r\sqrt{3}}{2}$. In our example, **r** is 1' 6", if we separate the cell centers by 1' 4" we achieve maximal coverage. Two cells arranged in this manner cover a maximal lineal distance of 5' 8". Four cells can cover a rhombic region 5' 8" by 5'8". An arrangement of 20 cells (five rows of four cells) permits the coverage of an area 11' 2" x 14', exceeding the tracking region of UNC's tracker.

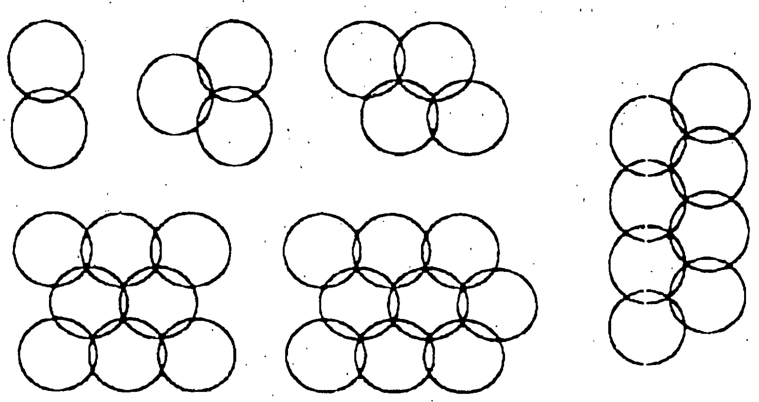

Figure 4. Cell layouts for achieving large area coverage.

Alignment and Calibration

Before using the cellular tracker, we must construct a single coordinate frame across all cells. One technique is to assemble the sources so they all lie carefully oriented and in a single plane. Then, by physically measuring the translational offsets between sources, we can construct a common coordinate frame. This process of assembly and measurement is, of necessity, an exacting and labor intensive process prone to introducing fairly large systematic errors.

Another approach is to use the partially working tracker itself to measure the pairwise relative position and orientation of adjacent cells. From the pairwise positions and orientations, we can construct a common coordinate frame. We use this latter approach.

We first need to define some basic terms and symbols before discussing how we construct the common coordinate frame. We use D_C to represent the position and orientation of the detector relative to a particular cell's coordinate frame. The matrix D_C encodes orientation as three direction cosines and position as a three vector displacement. We use the notation T_{AB} to represent a transformation from coordinate system B into coordinate system A. By evaluating:

$$D_R = T_{RC} \cdot D_C$$

we translate the position-orientation matrix D_c from cell C's coordinate frame into cell R's coordinate frame.

Static Alignment

We begin static alignment by first assigning a unique number to each cell. We choose one cell, say C_1, as the cell that defines the cellular tracker's coordinate frame. We place our detector in the overlap region between the root cell (C_1) and an adjacent cell (C_2) and measure the detector's position and orientation with respect to the root cell (D_{C_1}) and the adjacent cell (D_{C_2}). From these two measurements we compute a transform matrix that can transform measurements, made relative to one cell, into measurements relative to the other cell. That transformation matrix is computed as follows:

$$T_{C_1C_2} = D_{C_1} \cdot D_{C_2}^{-1}$$

We associate this matrix with cell C_2. Thereafter, before that cell returns a position-orientation measurement, it pre multiplies the measured position-orientation matrix with its stored transformation matrix.

We repeat this alignment process for each of the remaining cells. The more general problem of registering the tracker's coordinate system with the virtual world's coordinate system and the physical world's coordinate system is beyond the scope of this paper see [Janin, Mizell and Caudell 93] for a description of the process.

Cell Switching

Deciding when to switch from one cell to another requires carefully tracking the detector's position over time. From time-indexed position information, we can compute the detector's velocity. Similarly, we can compute the detector's acceleration from time-indexed velocities. Knowing the detector's position, velocity, and acceleration we can predict when the detector will move from being mainly inside one cell to being mainly inside an adjacent cell. The cell switching decision must include a slight amount of hysteresis to prevent oscillations.

System Precision and Accuracy

The system's precision and accuracy reduce as the square root of the distance (number of cells) from the root cell. Thus, assuming our rectangular arrangement of 20 cells (five rows of four cells) that cover a region 11' 2" x 14' and assuming we choose one corner as the system's root coordinate system, the translational precision along the column drops to $0.3\sqrt{4}$ mm or 0.6mm, the translation precision along the row drops to $0.3\sqrt{5}$ or 0.67mm, and the translation precision along the diagonal drops to $0.3\sqrt{6}$ or 0.73mm. Worst case (the diagonal) the tracker's translation precision is 0.73mm with an accuracy of 1.7mm; its rotational precision at 3 feet is 0.14° with an accuracy of 0.36° and at 6 feet its rotation precision drops to 0.28° with an accuracy of 0.72°.

By choosing the central cell as the system's root cell, we can improve worst-case precision and accuracy because we reduce the cell-distance from the root cell. The furthest cell is a cell distance of 4 cells from the root resulting in a system error a factor of $\sqrt{4}$ worse than a single cell. Thus, translation precision is 0.6mm with an accuracy of 0.14mm and rotational precision at 3 feet is 0.12° with an accuracy of 0.3° and at 6 feet rotational precision is 0.22° with an accuracy of 0.6°

Dynamic alignment

We can alternatively perform on-the-fly or dynamic cell alignment. Dynamic alignment is adapted directly from the static alignment technique. Whenever a detector is in range of two or more cells, we can measure the detector's position-orientation with respect to one cell and then, in the next time interval, with respect to the adjacent cell. These two measurements permit us to construct a transform matrix.

Though the dynamic alignment technique is conceptually quite simple, its implementation requires considerable care. We cannot make two simultaneous measurements of the detector from two adjacent cells and rarely will a detector stay at the same position-orientation over the interval of time needed to take the two consecutive measurements. This requires the system to track the detector's trend information fairly carefully, specifically position-orientations, velocities, and accelerations. Using this information and knowing the measurement rate, we can predict a detector's future position-orientation at the time that we take the second measurement. We can improve the transformation matrix iteratively by continually switching between cells whenever the detector is in a cell overlap region and recomputing the transform. Admittedly, a dynamically aligned cellular tracker will not have the precision or accuracy of a statically aligned tracker.

Multiple Detectors

The Logitech controller can track up to four detectors simultaneously with one source. The cellular system can also track multiple detectors, if all the detectors are in the same cell. As an example, a cell can easily track a user's head and right arm at the same time. However, if the user's head stays inside one cell while his arm moves into an

adjoining cell, we have a problem. Either we need to stop tracking the user's arm or we need to use a method for tracking detectors in adjoining cells. In applications where we can feasibly stop tracking one detector our problem reduces to deciding which detector takes precedence. In applications where we must continue tracking both detectors, we can do so by time-division multiplexing adjacent cells.. In the two cell case, we track one detector inside the first cell at even time intervals and we track the second detector inside the second cell at odd time intervals. If necessary, time-division multiplexing can work across more cells; however, not without a price. Time-division multiplexing reduces a cell's measurement rate. If the tracker is multiplexing two cells, update rates are halved, dropping from 50Hz to 25Hz. Multiplexing across three cells reduces the measurement rate to 16Hz and four cells reduces the rate to 12Hz—a barely acceptable measurement rate.

Conclusions and Future Directions

An AR system requires high-precision tracking so that it can position its virtual objects accurately within the physical surroundings and make those objects appear to remain stationary even when the user moves or rotates his head. A measurement error of a single degree can displace a virtual object by a substantial amount. Positioning objects accurately with respect to the physical surroundings requires good registration between the physical coordinate frame and the 6DOF tracker's coordinate frame. Keeping virtual objects from spurious displacements requires the 6DOF tracker to perform its measurements precisely.

We have presented a design for a low-cost, large-volume, reasonably high-precision and high-accuracy cellular tracker. The stringent requirements of AR applications provided the main motivation for the tracking system. Though the system provides appropriate precision and accuracy for use in laboratory and less demanding prototype applications, we must continue to develop trackers that have higher precision and higher accuracies and work in large volumes.

We may be able to extract better resolution and accuracy by enlarging the separation between a source's three ultrasonic emitters. By enlarging the separating among the emitters we enlarge the system's baseline allowing a more accurate triangulation computation. It appear possible to enlarging the source's baseline without physically modifying the source triangles. Instead, we can modify the switch box so that two emitters from one source operate in conjunction with an emitter from an adjacent cell's source.

Acknowledgments

We would like to thank David Mizell and Thomas Caudell who began the AR effort at Boeing and without whom this problem would not have been posed; Michael Deering of Sun Microsystems, Inc. for catalyzing this work; Thomas King for measuring a Logitech tracker's precision and accuracy when operated in raw mode; Victor Fong, Ali Moayer and Laurent Piguet for working on the design and test of the switch box; and, Chris Esposito, Adam Janin, and Karel Zikan for their discussions and insight into large volume tracking.

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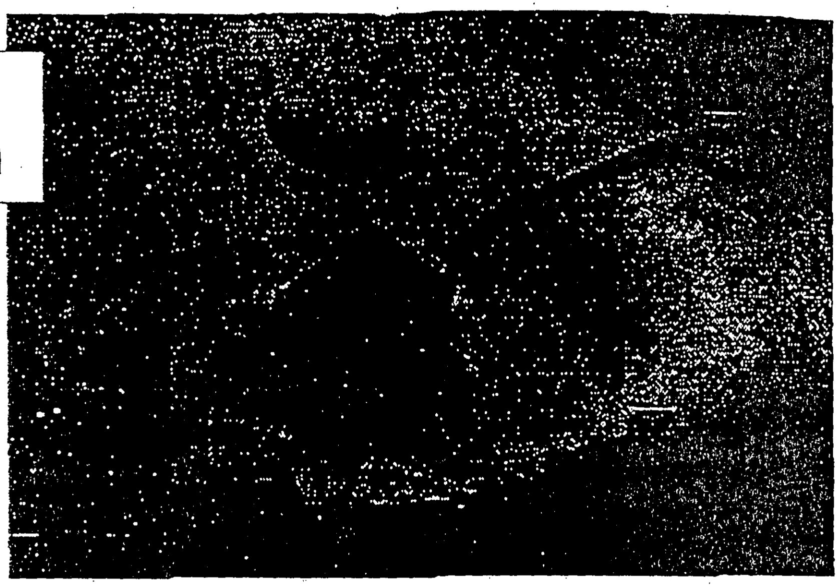
ANGULARIS VR-360
Inertial Tracking System



For High-Fidelity Sourceless VR Motion Tracking

Angularis proudly introduces the world's first and smallest inertial tracking system for advanced human machine interface applications. The VR-360 was designed to solve the difficult problem of tracking human head motion in immersive virtual environment and telepresence applications. Human subjects are extremely sensitive to inconsistencies caused by head-tracking systems. Existing magnetic, optical, acoustic, and sourceless gravimetric technologies have noticeable levels of latency, jitter, slosh, and distortion which distract the user and can cause simulator sickness. The VR-360 was designed to be sub-threshold in all these critical performance measures in order to deliver fast, smooth, consistent images to the user.

Applications

Although designed for Virtual Reality head-tracking, the potential applications of the VR-360 are limited only by your imagination:

- VR glove or hand-tracking
- gestural input and character animation
- intuitive manipulation of 3D graphical objects
- robot and teleoperator attitude control
- augmented reality systems
- biomechanics and psychophysics research

Works Anywhere

The VR-360 is sourceless and self-contained. 3-DOF orientation tracking may be accomplished with no setup or installation. It is immune to interference from optical, acoustic, magnetic, and RF sources, so it may be used in signal-cluttered environments. It also does not emit any signals that will interfere with other nearby instrumentation.

Small and Light

Using proprietary micro-miniature gyroscopes and accelerometers, Angularis has created the smallest and lightest 6-axis inertial sensor unit ever available. At just 1.6 cubic inches and under 3 ounces, the sensor would hardly be felt riding on an average 11 pound head.

Space-Age Inertial Technology

The VR-360 sensor unit contains 3 gyroscopes, 3 accelerometers, and a 2-axis magnetic compass, all implemented with fast-responding solid-state technology involving no moving parts. The system electronics box contains an inertial navigation computer which performs error compensation and adaptive Kalman filtering to obtain fast, smooth orientation and position updates at up to 500 Hz.

No Slosh or Drift

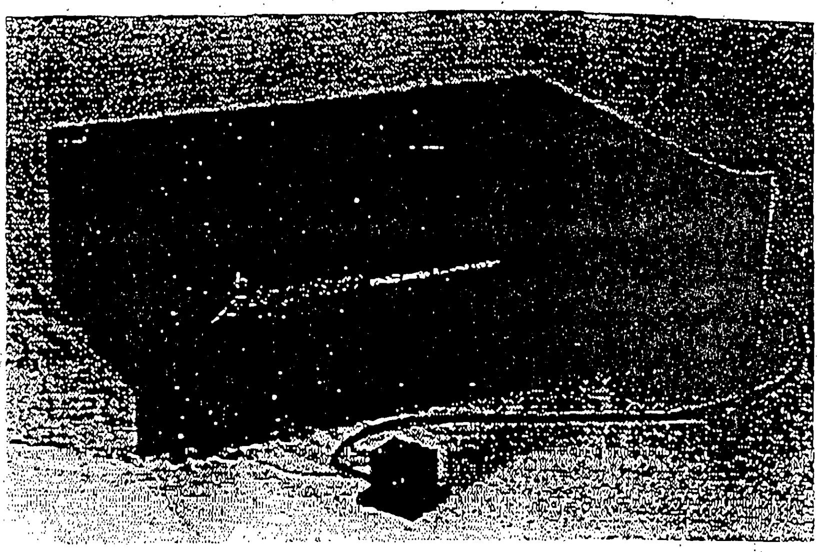
Simple gyroscopic orientation trackers are impractical for most VR applications due to drift. Sourceless compass and inclinometer orientation trackers used in many of today's low-cost HMDs do not have drift, but have a high degree of sensitivity to transverse acceleration ("slosh"). The VR-360 uses a patent pending technology developed at the Massachusetts Institute of Technology to obtain sourceless orientation measurement with no noticeable slosh or drift.

Fast and Predictive

The VR-360 contributes only 2 milliseconds of latency to your high-performance interactive system. Even more importantly, it is able to accurately predict motion up to 40 milliseconds in the future, thus partially compensating for graphics rendering delay.

Angularis Inertial Technologies
One Kendall Square, Suite 2200, Building 200
Cambridge, MA 02139
Telephone: (617)621-1563 Fax: (617) 577-1209

3-DOF and Hybrid 6-DOF Capability



The VR-360 may be used stand-alone for long-range sourceless 3-DOF orientation tracking. For 6-DOF operation, an external ultrasonic position tracker must be connected into the aux input jack of the VR-360 for positional drift compensation. Since the primary position measurement is inertial, with ultrasonic aiding data used only for drift compensation, noise and latency and even brief ultrasonic line-of-sight interruptions will not have catastrophic effects on the VR-360 positional tracking performance.

Compatible With Your Software

The VR-360 is equipped with a serial interface which uses the industry standard Polhemus*-compatible communications protocol. It will therefore work with existing applications which support the Polhemus Fastrak*. It is also equipped with a parallel port for faster communications in new applications.

* *Trademark of Polhemus Navigation Sciences, Inc.*

PRELIMINARY PRODUCT SPECIFICATIONS

ORIENTATION TRACKING

Max. Angular Rate:	1200 degrees per second
Latency:	<2 ms
Range:	all angles, 20' translation with standard cable, >50' with wireless upgrade kit
Max. Update Rate:	500 Hz
Prediction:	up to 40 ms
Resolution:	in testing, available soon
Accuracy:	in testing, available soon
Host intefaces:	rs-232c up to 115 kbaud, EPP parallel

POSITION TRACKING

(Requires external ultrasonic xyz tracker connected to rs-232c aux input jack)

External Position trackers supported:	Lipman Vscope 100 (wireless) Others to be supported soon.
Range:	same as ultrasonic (12' for Vscope)
Latency:	<2 ms
Update Rate:	up to 500 Hz
Prediction:	up to 40 ms
Resolution:	in testing, available soon
Accuracy:	in testing, available soon
Aux Input Interface:	RS-232 C up to 115 kbaud

SENSOR UNIT PHYSICAL SPECIFICATION

Dimension:	1.06" wide x 1.34" long x 1.20" high
Weight:	< 3 oz. (cable not included)
Cable:	20', 0.154" dia. with DB15 connector

TRACKER UNIT PHYSICAL SPECIFICATION

Dimension:	19" rack mount, 3 rack units high, 12" deep
Power:	115/230 VAC , 50/60 Hz; 4/2 A

Angularis Inertial Technologies

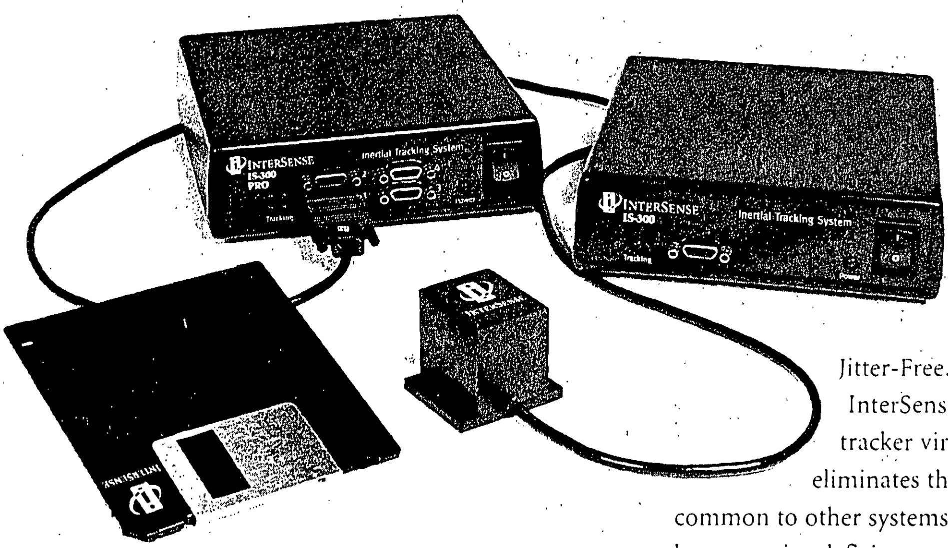
One Kendall Square, Suite 2200, Building 200, Cambridge, MA 02139, USA
Telephone (617)621-1563 Fax (617) 577-1209

INTERSENSE

IS-300 Precision Motion Tracker

Slow, jittery virtual environments are now a thing of the past.

For the first time, high-fidelity tracking with all the ease-of-use, freedom and robustness inherent in sourceless inertial technology is now possible. Simulator performance and realism are greatly enhanced with the IS-300 from InterSense.



Jitter-Free. The InterSense IS-300 tracker virtually eliminates the jitter common to other systems. This has been a major deficiency and source of simulator sickness in immersive head-mounted display applications.

Fast Response. The InterSense IS-300 offers industry leading update rates of up to 500 Hz, for the world's lowest latency tracking. Tracker-induced lag is removed from your virtual environment.

Distortion-Free. Our patented inertial sensing technology is not susceptible to the electromagnetic interference you've come to expect from competitive tracking technologies. So the InterSense IS-300 offers smooth, steady response, even in noisy, metal-cluttered environments.

Unlimited Range. The IS-300 is completely sourceless. This means no setup, no line-of-sight constraints and virtually unlimited operating range. The signal processor is small enough to wear on a belt for tetherless application.

Motion Prediction. The IS-300 Pro can predict motion up to 50 ms in the future, which compensates for graphics rendering delays and further contributes to eliminating simulator lag. InterSense is the *only* company to employ the proven benefits of inertial angular rate and acceleration sensors to provide accurate feed-forward motion prediction.

No Slosh or Drift. InterSense's proprietary micro-machined inertial sensor unit and signal processing virtually eliminates the sloshy response common to inclinometers and the accumulation of drift error that plagues ordinary gyroscopes.

Software Compatibility. If your application uses software that supports industry-standard trackers, you won't have to change a line of code to use the IS-300!

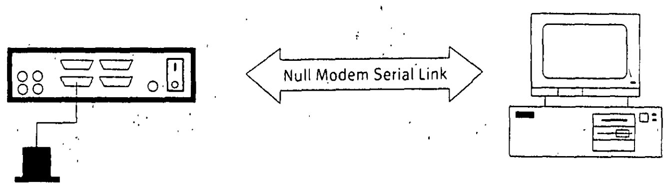
- **Fast & Smooth**
- **Motion Prediction**
- **Immune to Interference**
- **Unlimited Range**

INTERSENSE IS-300 Series

Technology Overview

The IS-300 obtains its primary motion sensing using a miniature solid-state inertial measurement unit (IMU) which senses angular rate of rotation, gravity and earth components along three perpendicular axes. The angular rates are integrated to obtain the orientation (yaw, pitch, and roll) of the sensor. Gravitometer and compass measurements are used to prevent the accumulation of gyroscopic drift.

Specifications



Degrees of Freedom Tracked	Yaw, pitch, and roll	
Angular Range	All orientations	
Maximum Angular Rate	1200°/sec	
Angular Resolution	0.02° RMS	
Static Accuracy	1° RMS	
Dynamic Accuracy	3° RMS	
	IS-300	**IS-300 Pro**
Number of Sensors	1	4
Prediction	NA	0-50 ms
Maximum Update Rate	150Hz	500Hz
Interface	RS-232C with selectable baud rates to 115,200	
Protocol	Compatible with industry-standard protocol	

Physical

Power	9-15 VDC, 8.6 W	
Operating Temperature	0 to 50°C	
Storage Temperature	-20 to 70°C	
	Sensor (IMU)	Signal Processor
Dimensions	1.06" x 1.34" x 1.2"	5.08" x 5.25" x 1.5"
Weight	2.1 oz.	15 oz.
Cable Length	10' extendible to 30'	NA

Compatibility

The InterSense IS-300 is compatible with all industry leading software and hardware, including products from:

- **Virtual Research**
- **Division**
- **SoftImage**
- **Sense8**
- **Superscape**
- **Multigen**
- **Accom Elset**
- **nVision**

More Information

Phone: 617-499-0020
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INTERSENSE INC.
160 SECOND STREET
CAMBRIDGE, MA
02142 USA

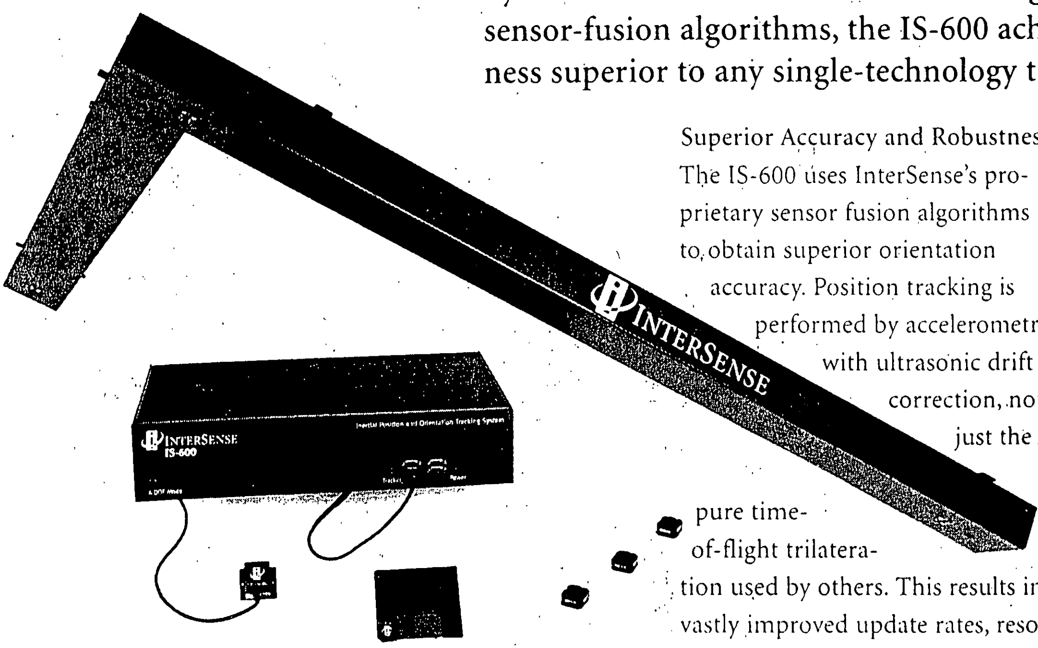
INTERSENSE
The Next Generation in Motion Tracking.

INTERSENSE

IS-600 Precision Motion Tracker

Robust 6 degree-of-freedom motion tracking for simulation and training.

For the first time, high-fidelity 6 Degree-of-Freedom (DOF) position and orientation tracking is possible without the limitations associated with all the other 6 DOF motion trackers on the market. By utilizing a hybrid of inertial and ultrasonic sensing technologies and proprietary sensor-fusion algorithms, the IS-600 achieves performance and robustness superior to any single-technology tracking device.



- **Fast & Smooth**
- **Motion Prediction**
- **Immune to Interference**

Superior Accuracy and Robustness. The IS-600 uses InterSense's proprietary sensor fusion algorithms to obtain superior orientation accuracy. Position tracking is performed by accelerometry with ultrasonic drift correction, not just the pure time-of-flight trilateration used by others. This results in vastly improved update rates, resolution, and immunity to ultrasonic interference.

Jitter-Free. The InterSense IS-600 tracker virtually eliminates the jitter common to other systems. This has been a major deficiency and source of simulator sickness in immersive head-mounted display applications.

Fast Response. The InterSense IS-600 provides update rates of up to 150Hz with extremely low latency. Tracker-induced lag is removed from your virtual environment.

Distortion-Free. Our patented inertial sensing technology is not susceptible to the electromagnetic interference you've come to expect from competitive tracking technologies. So the InterSense IS-600 offers smooth, steady response, even in noisy, metal-cluttered environments.

Motion Prediction. The IS-600 can predict motion up to 50 ms in the future, which compensates for graphics rendering delays and further contributes to eliminating simulator lag. InterSense is the *only* company to employ the proven benefits of inertial angular rate and acceleration sensors to provide accurate feed-forward motion prediction.

No Slosh or Drift. InterSense's proprietary micro-machined inertial sensor unit and signal processing virtually eliminates the sloshy response common to inclinometers and the accumulation of drift error that plagues ordinary gyroscopes.

Software Compatibility. If your application uses software that supports industry-standard trackers, you won't have to change a line of code to use the IS-600!

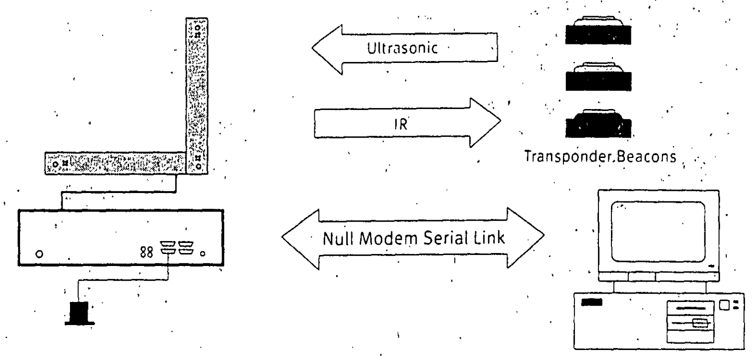
INTERSENSE IS-600

Technology Overview

The IS-600 obtains its primary motion sensing using a miniature solid-state inertial measurement unit (IMU) which senses angular rate of rotation and linear acceleration along three perpendicular axes. The angular rates are integrated to obtain the orientation (yaw, pitch, and roll) of the sensor, and the linear accelerations are transformed into a reference coordinate frame and double-integrated to keep track of changes in position (x, y, and z). Ultrasonic time-of-flight distance measurements are used to obtain a starting position and to correct any drift in the inertial position and orientation tracking.

Specifications

Maximum Angular Rate	1200°/sec
Angular Resolution	0.02° RMS
Angular Accuracy	0.25° RMS
Maximum Linear Velocity	15'/sec
Translation Resolution	0.01" RMS
Translation Accuracy	0.25" RMS
Prediction	0-50 ms
Number of Sensors	up to 4
Update Rate	up to 150Hz
Interface	RS-232C with selectable baud rates to 115,200
Protocol	Compatible with industry-standard protocol



Physical

Power	110 or 220 VAC, 100W
Operating Temperature	0 to 50°C
Storage Temperature	-20 to 70°C

	Sensor (IMU)	Transponder Beacons	Light Bar	Signal Processor
Dimensions	1.06" x 1.34" x 1.2"	1.5" x 1.5" x 0.75"	42.5" x 3.5" x 2" each leg	16.75" x 12" x 4"
Weight	2.1 oz.	3.5 oz.	6.8 lb.	9.2 lb.
Cable Length	10' extendible to 30'	NA	10'	NA

Compatibility

The InterSense IS-600 is compatible with all industry leading software and hardware, including products from:

- **Virtual Research**
- **Division**
- **SoftImage**
- **Sense8**
- **Superscape**
- **Multigen**
- **Accom Elset**
- **nVision**

More Information

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INTERSENSE INC.
160 SECOND STREET
CAMBRIDGE, MA
02142 USA

INTERSENSE
The Next Generation in Motion Tracking.

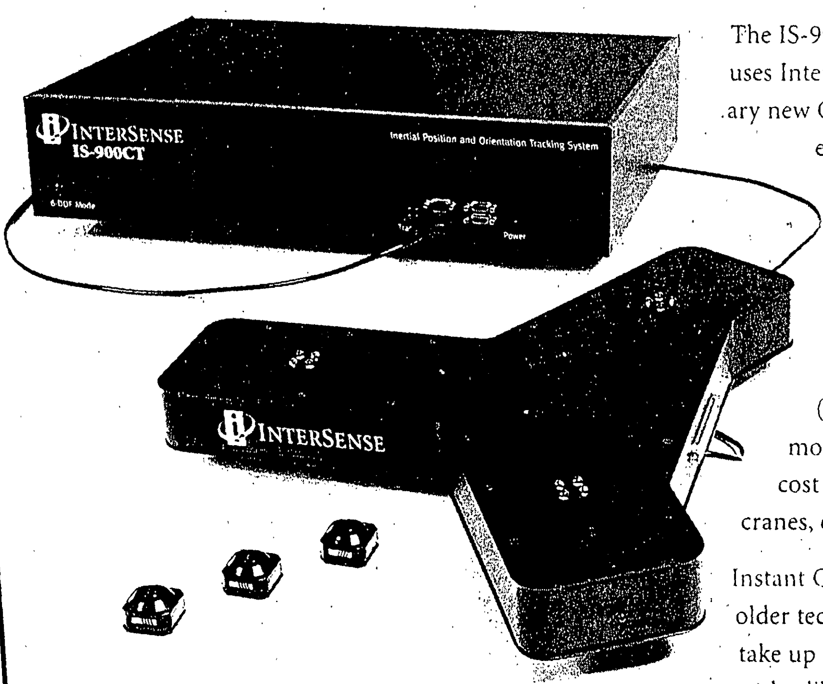
INTERSENSE

IS-900CT Camera Tracker

PRELIMINARY DATA SHEET

Creativity is returned to the director.

For the first time, virtual set and film cameras can be moved and tracked as easily as traditional cameras. The television and film industries can now utilize the boundary expanding capabilities of computer generated virtual sets and/or special effects and still maintain the creative control of camera position they are accustomed to.



The IS-900CT camera tracker uses InterSense's revolutionary new CONSTELLATION™ expandable motion tracking technology to provide producers with the ability to make unrestrained use of 6 degree-of-freedom (DOF) camera motion at a far lower cost than sensorized cranes, dollies and tripods.

Instant Calibration. Unlike older technologies that can take up to half-an-hour to set up and calibrate, InterSense's CONSTELLATION™ technology allows instantaneous calibration. Just push a button and you're ready to go.

Hand-Held Cameras. Today's dynamic cinematography techniques demand total camera flexibility. Older technologies require that the camera remain in a fixed position, limiting the range of possibilities. But InterSense gives you complete creative freedom to move the camera or even use hand-held cameras.

Software Compatibility. If your CG software supports industry standard trackers, you will be able to use InterSense's camera trackers.

- **Creative Freedom**
- **Hand-Held Cameras**
- **Instant Calibration**
- **6 Degree-of-Freedom**

INTERSENSE

IS-900CT Camera Tracker

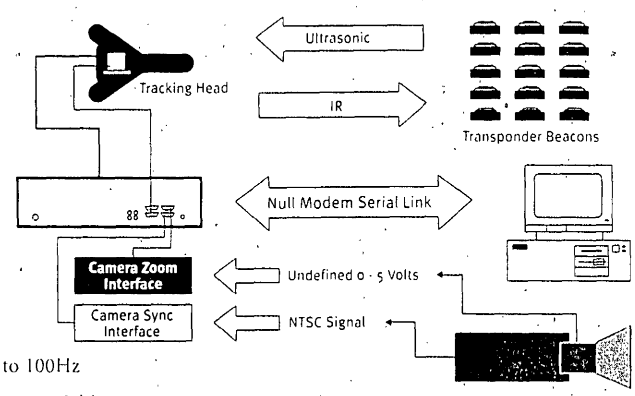
PRELIMINARY DATA

Technology Overview

The IS-900CT Camera Tracker obtains its primary motion sensing using a miniature solid-state inertial measurement unit (IMU) which senses angular rate of rotation and linear acceleration along three perpendicular axes. The angular rates are integrated to obtain the orientation (yaw, pitch, and roll) of the sensor, and the linear accelerations are transformed into a reference coordinate frame and double-integrated to keep track of changes in position (x, y, and z). Ultrasonic time-of-flight distance measurements are used to obtain a starting position and to correct any drift in the inertial position and orientation tracking.

Ultrasonic range measurements are made with respect to an array of wireless range transponder beacons. The array is positioned over the required camera movement area or on a wall behind the camera, or both. The beacons are triggered by beacon-specific infrared triggering codes, and they respond by emitting an ultrasonic chirp, which propagates through the air. Three ultrasonic receiver modules (URMs) mounted in one unit on the camera then detect this chirp. The URMs and associated electronics on the camera measure the time-of-flight and thereby obtain range measurements from the camera to whatever beacons are nearby and visible.

Specifications



Maximum Angular Rate	1200°/sec
Angular Resolution	0.02° RMS
Angular Accuracy	0.25° RMS
Maximum Linear Velocity	15'/sec
Translation Resolution	0.01" RMS
Translation Accuracy	0.25" RMS
Prediction	0-60 ms
Update Rate	up to 150Hz
Genlock Input	NTSC video, or TTL pulse from 20 to 100Hz
Zoom Input	Compatible with selected Fujinon lenses, 12-bit res.
Interface	RS-232C with selectable baud rates to 115,200
Protocol	Compatible with industry-standard protocol
H Tracking Range	Anywhere below the array of beacons.
V Tracking Range	1' to 10' below the array of beacons.

Physical

Power	110 or 220 VAC, 100W
Operating Temperature	0 to 50°C
Storage Temperature	-20 to 70°C

	Sensor Head	Transponder Beacons	Signal Processor
Dimensions	L 12" x W 14.7" x H 1.5"	1.5" x 1.5" x 0.75"	16.75" x 12" x 4"
Weight	3.0 lb.	3.5 oz.	9.2 lb.
Cable Length	30'	NA	NA

More Information

Phone: 617-499-0020
Fax: 617-492-1635
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INTERSENSE INC.
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INTERSENSE
The Next Generation in Motion Tracking.

Transaction History Date 1999-06-15
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

UNITED STATES DEPARTMENT OF COMMERCE
Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231

SERIAL NUMBER	FILING DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO.
09/062,442	04/17/98	FOXLIN	E 09970002001

QM41/0615

DAVID L FEIGENBAUM
FISH & RICHARDSON
225 FRANKLIN STREET
BOSTON MA 02110-2804

EXAMINER	
MARMOR II,C	
ART UNIT	PAPER NUMBER
3736	6

DATE MAILED: 06/15/99

Please find below a communication from the EXAMINER in charge of this application.

Commissioner of Patents

Office Action Summary	Application No. 09/062,442	Applicant(s) Foxlin
	Examiner Charles Marmor, II	Group Art Unit 3736

☐ Responsive to communication(s) filed on ______.

☐ This action is **FINAL.**

☐ Since this application is in condition for allowance except for formal matters, **prosecution as to the merits is closed** in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11; 453 O.G. 213.

A shortened statutory period for response to this action is set to expire 3 month(s), or thirty days, whichever is longer, from the mailing date of this communication. Failure to respond within the period for response will cause the application to become abandoned. (35 U.S.C. § 133). Extensions of time may be obtained under the provisions of 37 CFR 1.136(a).

Disposition of Claims

☒ Claim(s) *1-15* is/are pending in the application.

Of the above, claim(s) ______ is/are withdrawn from consideration.

☒ Claim(s) *10-13* is/are allowed.

☒ Claim(s) *1-6, 8, 9, and 14* is/are rejected.

☒ Claim(s) *7 and 15* is/are objected to.

☐ Claims ______ are subject to restriction or election requirement.

Application Papers

☐ See the attached Notice of Draftsperson's Patent Drawing Review, PTO-948.

☐ The drawing(s) filed on ______ is/are objected to by the Examiner.

☐ The proposed drawing correction, filed on ______ is ☐approved ☐disapproved.

☐ The specification is objected to by the Examiner.

☐ The oath or declaration is objected to by the Examiner.

Priority under 35 U.S.C. § 119

☐ Acknowledgement is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d).

☐ All ☐ Some* ☐ None of the CERTIFIED copies of the priority documents have been

☐ received.

☐ received in Application No. (Series Code/Serial Number) ______.

☐ received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

*Certified copies not received: ______.

☐ Acknowledgement is made of a claim for domestic priority under 35 U.S.C. § 119(e).

Attachment(s)

☒ Notice of References Cited, PTO-892

☒ Information Disclosure Statement(s), PTO-1449, Paper No(s). 5

☐ Interview Summary, PTO-413

☐ Notice of Draftsperson's Patent Drawing Review, PTO-948

☐ Notice of Informal Patent Application, PTO-152

--- SEE OFFICE ACTION ON THE FOLLOWING PAGES ---

DETAILED ACTION

Drawings

1. The drawings are objected to as failing to comply with 37 CFR 1.84(p)(5) because they include the following reference sign(s) not mentioned in the description: **1220** as illustrated in Fig. 12. Correction is required.

Specification

2. The disclosure is objected to because of the following informalities:

a. On page 3, line 15, the word "an" apparently should read --a--.

b. On page 4, line 29, the word "block" apparently should read --blocked--.

c. On page 10, line 5, the word --to-- apparently should be inserted before the word "one".

d. On page 16, line 9, reference number "**850**" apparently should read --**860**--.

e. On page 28, line 27, the word "increase" apparently should read --increased--.

Appropriate correction is required.

3. The lengthy specification has not been checked to the extent necessary to determine the presence of all possible minor errors. Applicant's cooperation is requested in correcting any errors of which applicant may become aware in the specification.

Claim Objections

4. Claim 5 is objected to because of the following informalities: on line 7, the word "wither" apparently should read --either--. Appropriate correction is required.

Claim Rejections - 35 USC § 112

5. The following is a quotation of the second paragraph of 35 U.S.C. 112:

> The specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the applicant regards as his invention.

6. Claim 9 is rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. Applicant appears to be claiming a method step from the language of the claim, thereby mixing two statutory classes of invention.

Claim Rejections - 35 USC § 102

7. The following is a quotation of the appropriate paragraphs of 35 U.S.C. 102 that form the basis for the rejections under this section made in this Office action:

> A person shall be entitled to a patent unless --
>
> (b) the invention was patented or described in a printed publication in this or a foreign country or in public use or on sale in this country, more than one year prior to the date of application for patent in the United States.

8. Claims 1-6,8,9, and 14 are rejected under 35 U.S.C. 102() as being anticipated by Horton et al. Horton et al. teaches an apparatus and method for determining the position and orientation of a moveable object. Two types of measurements associated with the motion of the body are obtained: inertial measurements are obtained by accelerometers **1-6** and acoustic ranging measurements are obtained by acoustic/ultrasonic external tracking system **170.** The measurements are received by a tracking processor **40**. The two types of measurements are used to update an estimate of an orientation or a position of the body.

Allowable Subject Matter

9. Claims 10-13 are allowable over the prior art of reference.

10. Claims 7 and 15 are objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

Conclusion

11. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure. Nachman et al. teach a moored ship motion determination system using two types of measurements associated with the motion of a ship. Kramer teaches devices and methods for the accurate reporting of movement of an entity using at least two types of measurements associated with the motion of the body. Sieber et al. teach a smart tracking system including a digital processor for selectively processing error signals representing the angular error between a tracked subject and the orientation of the tracking device. Foxlin teaches an inertial orientation tracker having automatic drift compensation for tracking the human head and other similarly sized bodies. Mogavero et al. teach a system and method for tracking a moving signal source. Darrow et al. teach a tracking system for monitoring the position of an interventional device in a non-stationary subject. Taylor et al. teach a signaling device and method for monitoring positions in a surgical operation. Parker et al. teach a remote-controlled tracking system for tracking a remote control unit and positioning a camera.

12. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Charles Marmor, II whose telephone number is (703)305-3521. The examiner can normally be reached Monday - Thursday from 7:30am - 5:00pm. Additionally, the SPE for Art Unit 3736 is Cary O'Connor whose phone number is (703)308-2701, and the group's central fax number is (703)305-3590.

Any inquiry of a general nature or relating to the status of this application should be directed to the group receptionist whose telephone number is (703)308-0858. The fax number for Art Unit 3736 is (703)308-0758.

Cary O'Connor
CARY O'CONNOR
SUPERVISORY PATENT EXAMINER
GROUP 3700

CAM
CAM

June 7, 1999

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 1999-06-15

Document Title - List of references cited by examiner

PATENT
ATTORNEY DOCKET NO. 01997/238001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No.: 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit: 3737
Examiner: MARMOR II, C.

Assistant Commissioner for Patents
Washington, DC 20231

RESPONSE TO ACTION DATED JUNE 15, 1999

Please amend the application as follows.

In The Specification:

Page 2, line 5, change "a bias a" to --a bias to--.

Page 3, line 15: change "an" to --a--.

Page 4, line 29, change "block" to --blocked--.

Page 10, line 5, insert --to-- before the word "one".

Page 16, line 9, change "850" to --860--.

Page 25, line 11, change "expect" to --expected--.

Page 28, line 27, change "increase" to --increased--.

Page 29, line 26, change "addition" to --additional--.

Page 31, line 16, change "is" to "are".

Page 33, line 5, change "it's" to --its--.

Page 33, line 7, change "search" to --searching--.

Page 33, line 11, change "is determined" to --is in is determined--.

In the claims:

Please cancel claim 3 without prejudice.

Please amend the remaining claims as follows:

12/23/1999 SLUANG 00000029 09062442
02 FC:199 1110.00 OP

A

Date of Deposit 12·15·99
I hereby certify under 37 CFR 1.8(a) that this correspondence is being deposited with the United States Postal Service as **first class mail** with sufficient postage on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Kesley J. Asciutto

(All claims are shown, with the status of each claim indicated after the claim number.)

1. (amended) A method for tracking a motion of a body comprising:

a1

obtaining [two] three types of measurements associated with the motion of the body, [one of the types] a first type comprising acoustic measurement, a second type comprising linear inertial measurement, and a third type comprising angular inertial measurement;

updating an estimate of [either an orientation or] a position of the body based on the second type of measurement [based on one of the two types of measurement]; [and]

updating the position estimate based on [the other of the two types of measurement] the first type of measurement; and

updating an estimate of an orientation of the body based on the third type of measurement.

2. (amended) The method of claim 1 in which [one of the] the first type[s] of measurement comprises acoustic ranging.

3. (cancelled)

3. ~~4~~. (amended) The method of claim 1 in which the estimate [is] of orientation is updated based on the first type of measurement.

a2

4. ~~5~~. (amended) An apparatus for tracking motion of a body comprising:

[two] three sensor systems configured respectively to obtain [two] three types of measurements associated with motion of the body, [one of the types] a first type comprising acoustic

39

A

measurement, a second type comprising linear inertial measurement and a third type comprising angular inertial measurement; and

a processor coupled to the [two] three sensor systems and configured to update an estimate of [wither an orientation or] a position of the body based on the second type of measurement [based on one of the two types of measurement], [and] to update the position estimate based on the [other of the two types of measurement] the first type of measurement, and to update an estimate of an orientation of the body based on the third type of measurement.

A2 cont

6. (unchanged) A tracking device comprising:

a sensor system including

an inertial sensor; and

a set of one or more acoustic sensors rigidly coupled to the inertial sensor; and

a processor programmed to perform the functions of

accepting inertial measurements from the inertial sensor;

updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements;

selecting one of a plurality of acoustic reference devices;

accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device;

updating the location estimate and the orientation

40

A

estimate using the accepted range measurement.

7. (unchanged) The tracking device of claim 6 wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device.

8. (unchanged) The tracking device of claim 6 wherein the set of one or more acoustic sensors includes two or more acoustic sensors.

8. ~~9~~. (amended) The tracking device of claim 5 ~~6~~ wherein the processor is configured to

updat[ing]e a location estimate and an orientation estimate using the accepted inertial measurements by [includes] updating an uncertainty in the location and the orientation estimates; and

updat[ing]e the location estimate and the orientation estimate using the accepted range measurement by [includes] determining an uncertainty in the range measurement[,] and updating the uncertainty in the location and the orientation estimates using the uncertainty in the range measurement.

Q3

9. ~~10~~. (amended) A method for tracking the motion of a body including:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving a[n] range measurement signal from the

41

A

reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

A3 Cont.

11. (unchanged) The method of claim 10 further comprising:

determining a range measurement based on a time of flight of the range measurement signal.

12. (unchanged) The method of claim 10 wherein transmitting the control signal includes transmitting a wireless control signal.

~~13~~. (amended) Software stored on a computer readable medium comprising instructions for causing a computer to perform the functions of:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving a[n] range measurement signal from the reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

A4

14. (unchanged) A tracking system comprising:

an acoustic reference system including a plurality of acoustic reference devices; and

42

A

a tracking device including

a sensor system including an inertial sensor and a set of one or more acoustic sensors rigidly coupled to the inertial sensor, and

a processor programmed to perform the functions of accepting inertial measurements from the inertial sensor, updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements, selecting one of a plurality of acoustic reference devices, accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device, and updating the location estimate and the orientation estimate using the accepted range measurement.

15. (unchanged) The system of claim 14 wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device, and wherein each acoustic reference device includes a receiver for receiving the control signal from the sensor system, and an acoustic transducer for sending the acoustic signal.

Please add the following new claims:

12 ~~16~~. The method of claim ~~10~~ 9, further comprising:

a5

obtaining an inertial measurement; and

updating the location estimate or orientation estimate based on the inertial measurement.

17. An apparatus for tracking motion of a body

A

comprising:

two sensor systems configured respectively to obtain two types of measurements associated with motion of the body, one of the types comprising acoustic measurement, wherein the sensor system for obtaining acoustic measurement comprises greater than three acoustic receivers; and

a processor coupled to the two sensor systems and configured to update an estimate of either an orientation or a position of the body based on one of the two types of measurement, and to update the estimate based on the other of the two types of measurement.

18. The apparatus of claim 17, wherein one of the types of measurement comprises acoustic ranging.

19. The apparatus of claim 17, in which the other of the types of measurement comprises inertial measurement.

20. The apparatus of claim 17 in which the processor is configured to update an estimate of orientation based on the first type of measurement.

21. The apparatus of claim 20 in which the processor is configured to update an estimate of position based on the first type of measurement.

16 ~~22~~. The system of claim 14, further comprising more than three acoustic receivers.

22 ~~23~~. A method for tracking the motion of a body including:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference

44

device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

23. ~~24~~. The method of claim 22 ~~23~~ further comprising:

receiving a range measurement signal from the selected reference device; and

determining a range measurement based on a time of flight of the range measurement signal.

24. ~~25~~. The method of claim 22 ~~23~~ wherein transmitting the control signal includes transmitting a wireless control signal.

25. ~~26~~. Software stored on a computer readable medium comprising instructions for causing a computer to perform the functions of:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

26. ~~27~~. A tracking device comprising:

a sensor system including

an inertial sensor; and

a set of one or more acoustic sensors rigidly coupled to the inertial sensor; and

a processor programmed to perform the functions of

accepting inertial measurements from the inertial sensor;

updating a location or orientation estimate of the sensor system using the accepted inertial measurements;

selecting one of a plurality of acoustic reference devices;

accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device;

updating the estimate using the accepted range measurement.

as amt

27. ~~28~~. The tracking device of claim 26, ~~27~~ wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the selected acoustic reference device.

28. ~~29~~. The tracking device of claim 26, ~~27~~ wherein the set of one or more acoustic sensors includes two or more acoustic sensors.

29. ~~30~~. The tracking device of claim 26, ~~27~~ wherein the set of one or more acoustic sensors includes more than three acoustic sensors.

30. ~~31~~. The tracking device of claim 26, ~~27~~ wherein

the processor is configured to

update the estimate using the accepted inertial measurements by updating an uncertainty in the estimate; and

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update the estimate using the accepted range measurement by determining an uncertainty in the range measurement and updating the uncertainty in the estimate using the uncertainty in the range measurement.

31. ~~32~~. A tracking system for tracking the position of a body comprising:

a sensor system comprising a plurality of acoustic receivers rigidly coupled to a portable assembly; and

a plurality of acoustic reference devices arrayed at a distance from the portable assembly, wherein the acoustic receivers are arrayed on the portable assembly so that at least one of the acoustic receivers is positioned to receive signals from at least three of the acoustic reference devices regardless of the orientation of the portable assembly.

a5 cont

32. ~~33~~. The tracking system of claim 31, ~~32~~, wherein the plurality of acoustic receivers comprises greater than 3 receivers.

34. The tracking system of claim 31, ~~32~~, wherein for a majority of the orientations of the portable assembly, at least two of the acoustic receivers are positioned to receive signals from at least three of the acoustic reference devices.

33. ~~35~~. The system of claim 32, ~~33~~, further comprising a processor programmed to select, based on the current orientation of the portable assembly, a subset of the acoustic receivers according to their ability to receive signals from the acoustic reference devices.

35. ~~36~~. A method for tracking motion of a rigid body

comprising:

disposing a plurality of transducers in the environment;

mounting a plurality of transducers on the body;

measuring the range between a selected one of the transducers disposed in the environment and a selected one of the transducers mounted on the body;

predicting a range measurement between the selected transducer in the environment and the selected transducers mounted on the body;

updating an estimate of the orientation or position of the body based on the difference between the actual range measurement and the predicted range measurement.

a5 cont

36. ~~37~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are acoustic emitters and the transducers mounted on the body are acoustic receivers.

37. ~~38~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are acoustic receivers and the transducers mounted on the body are acoustic emitters.

38. ~~39~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are optical emitters and the transducers mounted on the body are optical receivers.

39. ~~40~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are optical receivers and the transducers mounted on the body are optical emitters.

40. ~~41~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are radio frequency emitters and the

transducers mounted on the body are radio frequency receivers.

41. ~~42~~. The method of claim 35, ~~36~~, wherein the transducers disposed in the environment are radio frequency receivers and the transducers mounted on the body are radio frequency emitters.

42. ~~43~~. The method of claim 35, ~~36~~, wherein at the transducers mounted on the body are disposed so that, in substantially all orientations of the rigid body, at least one of the transducers mounted on the body is positioned to be able to complete a range measurement with at least three of the transducers disposed in the environment.

a5 cont

43. ~~44~~. The method of claim 42, ~~43~~, further comprising:

selecting one of the transducers mounted on the body and obtaining a range measurement between it and one of the transducers disposed in the environment.

44. ~~45~~. A method for tracking a motion of a body comprising:

obtaining two types of measurements associated with the motion of the body, a first type comprising range measurement, and a second type comprising inertial measurement;

updating estimates of an orientation and a position of the body based on the second type of measurement; and

updating the estimate of the position of the body based on the first type of measurement, without first calculating a position estimate based only on the first type of measurement.

45. ~~46~~. The method of claim 44, ~~45~~ in which the first type of measurement comprises acoustic ranging.

46. ~~47~~. The method of claim 44, ~~45~~ further comprising updating

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the estimate of an orientation of the body based on the first type of measurement.

~~48~~ 47. A method for tracking a motion of a body comprising:

a5 cont

obtaining two types of measurements associated with the motion of the body, a first type comprising range measurement, and a second type comprising angular inertial measurement;

updating an estimate of an orientation of the body based on the second type of measurement; and

updating the orientation estimate and an estimate of the position of the body based on the first type of measurement.--

Remarks

Each of the applicant's additional remarks below is preceded by related comments from the examiner's action, in bold small type.

1. The drawings are objected to as failing to comply with 37 CFR 1.84(p)(5) because they include the following reference sign(s) not mentioned in the description: 1220 as illustrated in Fig. 12. Correction is required.

Applicant has removed the reference numeral 1220 by redmarking the attached proposed revision to Figure 12.

2. The disclosure is objected to because of the following informalities:

***

Appropriate correction is required.

The informalities identified by the Examiner have been corrected.

4. Claim 5 is objected to because of the following informalities: on line 7, the word "wither" apparently should read --either--. Appropriate correction is required.

Claim 5 has been amended.

> **6. Claim 9 is rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. Applicant appears to be claiming a method step from the language of the claim, thereby mixing two statutory classes of invention.**

Claim 9 has been amended.

> **8. Claims 1-6, 8, 9, and 14 are rejected under 35 U.S.C. 102() as being anticipated by Horton et al. Horton et al. teaches an apparatus and method for determining the position and orientation of a movable object. Two types of measurements associated with the motion of the body are obtained: inertial measurements are obtained by accelerometers 1-6 and acoustic ranging measurements are obtained by acoustic/ultrasonic external tracking system 170. The measurements are received by a tracking processor 40. The two types of measurements are used to update an estimate of an orientation or a position of the body.**

Claims 1 and 5 have been amended to make clear that angular inertial measurement is used to update an estimate of an orientation of the body. Horton describes a virtual reality tracking system using conventional linear accelerometers (col. 3:27-40). However, Horton neither discloses nor suggests using angular inertial measurement (e.g. measurement using angular accelerometers or gyroscopes) to update an estimate of the orientation of a body. To the contrary, Horton specifically rejects the use of gyroscopes and angular accelerometers as impractical for virtual reality applications (col. 1:46 - 2:3). According to Horton:

> [conventional] gyroscopes ... are not suitable for attachment to a human user because of their size and weight. In addition, these devices are typically designed to track over several hundred kilometers and several days, and are accurate only to several meters.
>
> Two-dimensional navigation systems using angular accelerometers (a type of gyroscope) ... are not suitable for virtual reality applications.... [A]ngular accelerometers are not easily integrated into electronic componentry, thus the resulting system is generally greater in size and weight and is not suitable for attachment to a human user.

(col. 1:46 - 2:1).

Claim 6 and 14 both require a processor programmed to select one of a plurality of acoustic reference devices, to accept an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device, and to update the location estimate and the orientation estimate using the accepted range measurement. Nothing in Horton et al. describes or suggests such a combination. The external tracking system 170 of Horton is a

> conventional tracking system using, for example, radar, sonar, infrared, optical, acoustic/ultrasonic, or magnetic tracking technology. External position, orientation, and/or velocity measurements 90 are provided in the form of a 1- to 2- dimensional update or a full 3-dimensional, 6 degree of freedom update.

(col. 8:45-52). Thus Horton teaches receiving pre-processed position, orientation, and/or velocity measurements from an external tracking system. Nothing in Horton teaches or suggests that this information should be generated by a process which entails selecting one of a plurality of acoustic reference devices and then accepting a range measurement related to the distance between the sensor system and the selected device.

9. Claim 10-13 are allowable over the prior art of reference.

Applicant acknowledges that claims 10-13 are allowable.

10. Claims 7 and 15 are objected to as being dependent upon a rejected base claim, but would be allowable if rewritten in independent form including all of the limitations of the base claim and any intervening claims.

Claim 7 and 15 and all other dependent claims not specifically discussed above are patentable for at least the same reasons as the independent claims from which they depend.

Applicant asks that all claims be allowed. If there are any charges or credits, please apply them to Deposit Account No. 06-1050, reference 01197-238001.

Respectfully submitted,

Date: 12/15/99

David L. Feigenbaum
Reg. No. 30,378
Lawrence K. Kolodney
Reg. No. 43,807

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804

Telephone: 617/542-5070
Facsimile: 617/542-8906
395785.B11

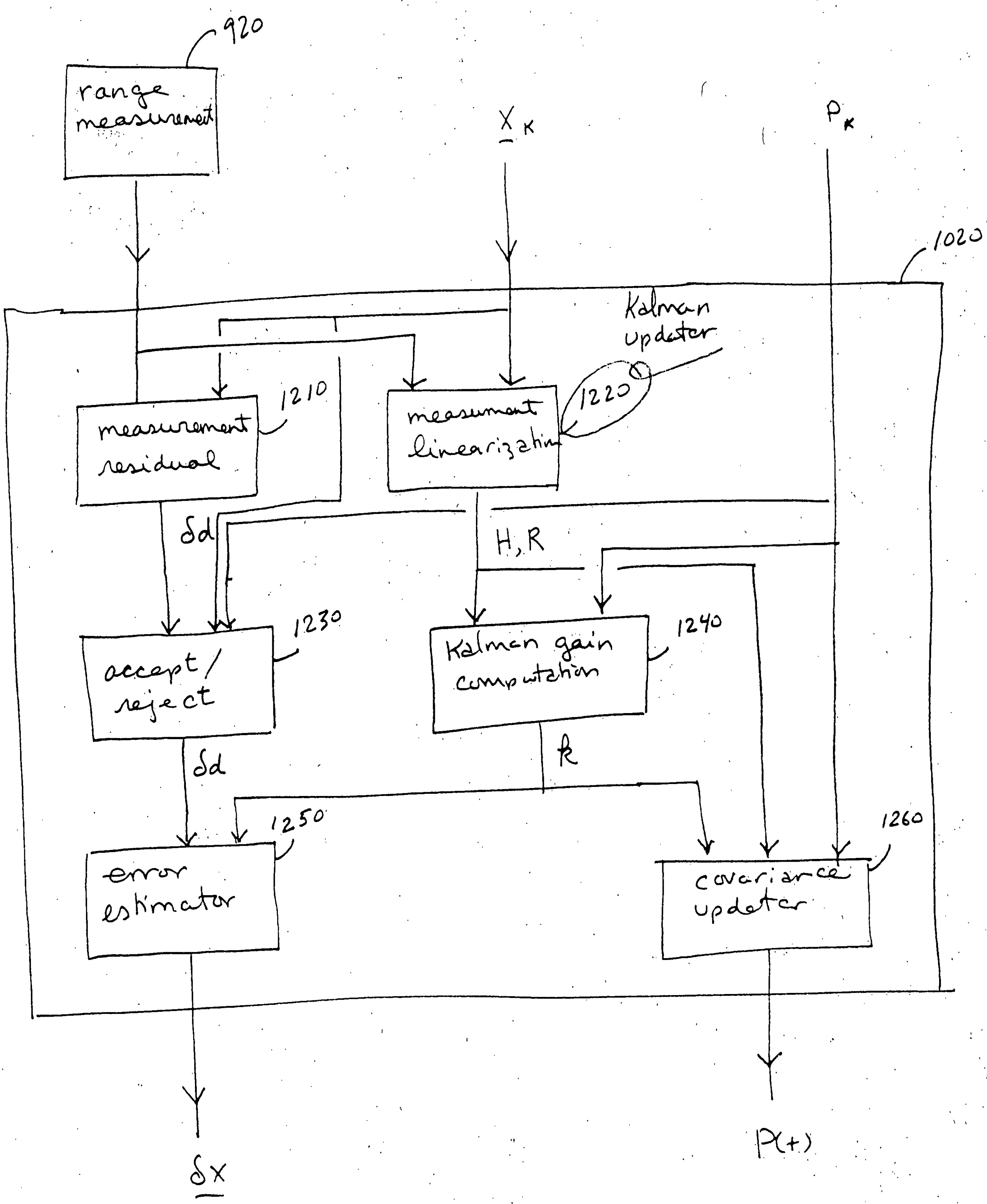
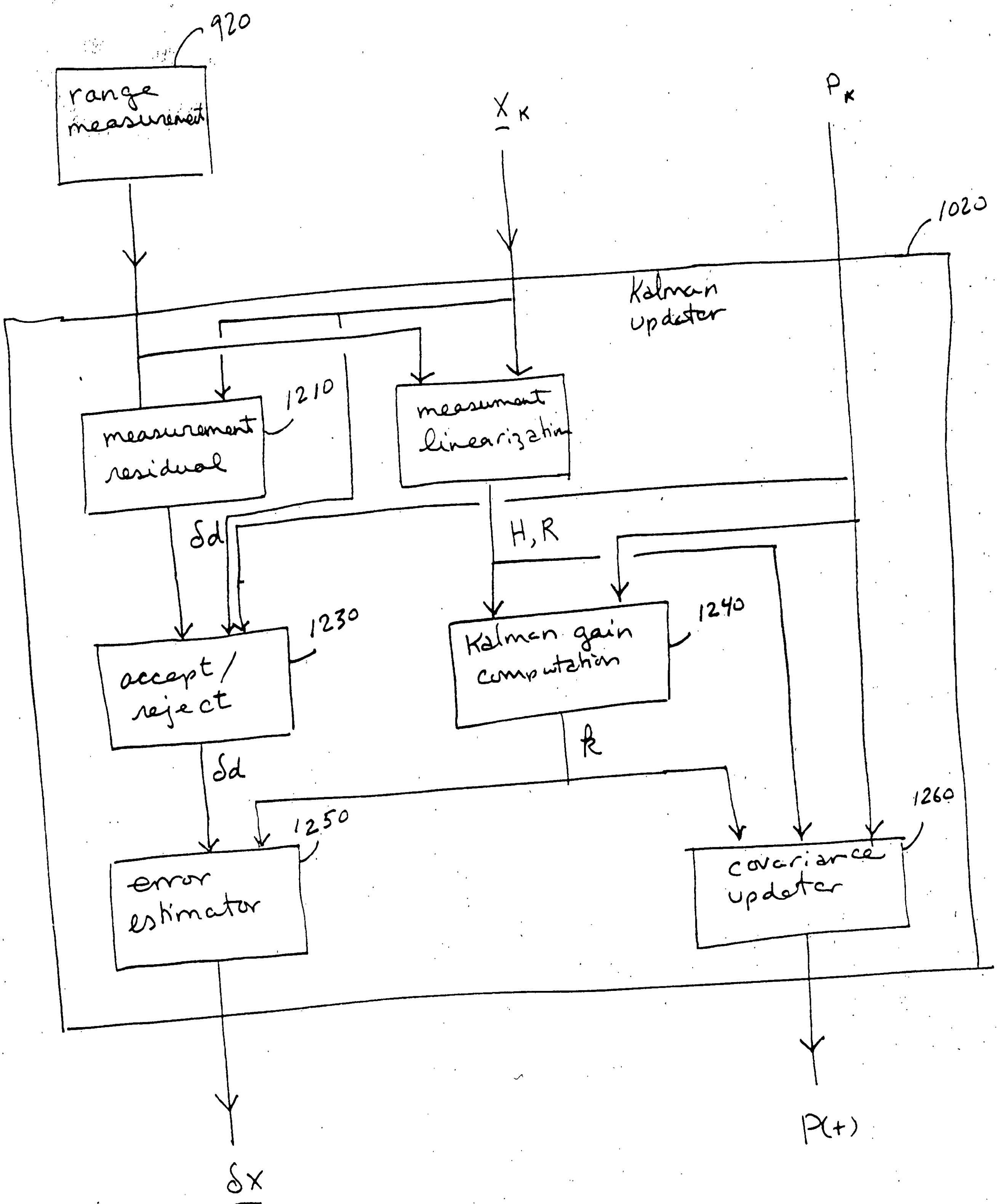

920
range measurement
$\underline{X}_K$
P_K
1020
Kalman updater
measurement residual
1210
measurement linearization
1220
δd
H, R
accept / reject
1230
Kalman gain computation
1240
k
δd
error estimator
1250
covariance updater
1260
$\underline{\delta x}$
P(+)

Fig. 12



920
range measurement
$\underline{X}_K$
P_K
1020
Kalman updater
measurement residual
1210
measurement linearization
δd
H, R
accept/reject
1230
Kalman gain computation
1240
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1250
error estimator
1260
covariance updater
$\underline{\delta x}$
P(+)

Fig. 12

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GP 3737 8

Attorney's Docket No.: 019? ?8001 / MIT Case 8226S

#7 A
Ext. of Time
12/30/99

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No. : 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit : 3737
Examiner : Marmor II, C

Assistant Commissioner for Patents
Washington, D.C. 20231

PETITION FOR THREE-MONTH EXTENSION OF TIME

Pursuant to 37 CFR §1.136, applicant hereby petitions that the period for response to the action dated June 15, 1999, be extended for three months to and including December 15, 1999.

Enclosed is a check for $870 for the required fee. Please apply any other charges or credits to Deposit Account No. 06-1050, reference 01997-238001.

Respectfully submitted,

Date: 12/15/99

David L. Feigenbaum
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20010396.doc

12/23/1999 SLUANG 00000029 09062442
01 FC:117 870.00 OP

CERTIFICATE OF MAILING BY FIRST CLASS MAIL

I hereby certify under 37 CFR §1.8(a) that this correspondence is being deposited with the United States Postal Service as first class mail with sufficient postage on the date indicated below and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

December 15, 1999
Date of Deposit

Lesley J. Arcidy
Signature

Lesley J. Arcidy
Typed or Printed Name of Person Signing Certificate

Transaction History Date 2000-03-09
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

Notice of Allowability	Application No. 09/062,442	Applicant(s) Foxlin
	Examiner Charles Marmor, II	Group Art Unit 3736

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance and Issue Fee Due or other appropriate communication will be mailed in due course.

☒ This communication is responsive to *the amendment filed on December 20, 1999*.

☒ The allowed claim(s) is/are *1,2, and 4-48 (renumbered claims 1-47)*.

☐ The drawings filed on ________ are acceptable.

☐ Acknowledgement is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d).

☐ All ☐ Some* ☐ None of the CERTIFIED copies of the priority documents have been

☐ received.

☐ received in Application No. (Series Code/Serial Number) ________.

☐ received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

*Certified copies not received: ________.

☐ Acknowledgement is made of a claim for domestic priority under 35 U.S.C. § 119(e).

A SHORTENED STATUTORY PERIOD FOR RESPONSE to comply with the requirements noted below is set to EXPIRE **THREE MONTHS** FROM THE "DATE MAILED" of this Office action. Failure to timely comply will result in ABANDONMENT of this application. Extensions of time may be obtained under the provisions of 37 CFR 1.136(a).

☐ Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL APPLICATION, PTO-152, which discloses that the oath or declaration is deficient. A SUBSTITUTE OATH OR DECLARATION IS REQUIRED.

☒ Applicant MUST submit NEW FORMAL DRAWINGS

☐ because the originally filed drawings were declared by applicant to be informal.

☒ including changes required by the Notice of Draftsperson's Patent Drawing Review, PTO-948, attached hereto or to Paper No. *8*.

☒ including changes required by the proposed drawing correction filed on *Dec 20, 1999*, which has been approved by the examiner.

☐ including changes required by the attached Examiner's Amendment/Comment.

Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the reverse side of the drawings. The drawings should be filed as a separate paper with a transmittal lettter addressed to the Official Draftsperson.

☐ Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Any response to this letter should include, in the upper right hand corner, the APPLICATION NUMBER (SERIES CODE/SERIAL NUMBER). If applicant has received a Notice of Allowance and Issue Fee Due, the ISSUE BATCH NUMBER and DATE of the NOTICE OF ALLOWANCE should also be included.

Attachment(s)

☐ Notice of References Cited, PTO-892
☐ Information Disclosure Statement(s), PTO-1449, Paper No(s). ________
☒ Notice of Draftsperson's Patent Drawing Review, PTO-948
☐ Notice of Informal Patent Application, PTO-152
☐ Interview Summary, PTO-413
☐ Examiner's Amendment/Comment
☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material
☐ Examiner's Statement of Reasons for Allowance

Cary O'Connor
CARY O'CONNOR
SUPERVISORY PATENT EXAMINER
GROUP 3700

Form PTO 948 (Rev. 8-98) U.S. DEPARTMENT OF COMMERCE - Patent and Trademark Office Application No. 062442

NOTICE OF DRAFTSPERSON'S PATENT DRAWING REVIEW

The drawing(s) filed (insert date) 4/17/98 are:

A. ☐ approved by the Draftsperson under 37 CFR 1.84 or 1.152.

B. ☒ objected to by the Draftsperson under 37 CFR 1.84 or 1.152 for the reasons indicated below. The Examiner will require submission of new, corrected drawings when necessary. Corrected drawing must be sumitted according to the instructions on the back of this notice.

1. DRAWINGS. 37 CFR 1.84(a): Acceptable categories of drawings:
   Black ink. Color.
   ____ Color drawings are not acceptable until petiton is granted.
   Fig(s) ____
   ____ Pencil and non black ink not permitted. Fig(s) ____
2. PHOTOGRAPHS. 37 CFR 1.84 (b)
   ____ 1 full-tone set is required. Fig(s) ____
   ____ Photographs not properly mounted (must use brystol board or photographic double-weight paper). Fig(s) ____
   ____ Poor quality (half-tone). Fig(s) ____
3. TYPE OF PAPER. 37 CFR 1.84(e)
   ____ Paper not flexible, strong, white, and durable.
   Fig(s) ____
   ____ Erasures, alterations, overwritings, interlineations, folds, copy machine marks not accepted. Fig(s) ____
   ____ Mylar, velum paper is not acceptable (too thin).
   Fig(s) ____
4. SIZE OF PAPER. 37 CFR 1.84(f): Acceptable sizes:
   ____ 21.0 cm by 29.7 cm (DIN size A4)
   ____ 21.6 cm by 27.9 cm (8 1/2 x 11 inches)
   ____ All drawing sheets not the same size.
   Sheet(s) ____
   ____ Drawings sheets not an acceptable size. Fig(s) ____
5. MARGINS. 37 CFR 1.84(g): Acceptable margins:
   Top 2.5 cm Left 2.5cm Right 1.5 cm Bottom 1.0 cm
   SIZE: A4 Size
   Top 2.5 cm Left 2.5 cm Right 1.5 cm Bottom 1.0 cm
   SIZE: 8 1/2 x 11
   Margins not acceptable. Fig(s) ____
   X Top (T) X Left (L)
   ____ Right (R) ____ Bottom (B)
6. VIEWS. 37 CFR 1.84(h)
   REMINDER: Specification may require revision to correspond to drawing changes.
   Partial views. 37 CFR 1.84(h)(2)
   ____ Brackets needed to show figure as one entity.
   Fig(s) ____
   X Views not labeled separately or properly.
   Fig(s) 5
   ____ Enlarged view not labeled separetely or properly.
   Fig(s) ____
7. SECTIONAL VIEWS. 37 CFR 1.84 (h)(3)
   ____ Hatching not indicated for sectional portions of an object.
   Fig(s) ____
   ____ Sectional designation should be noted with Arabic or Roman numbers. Fig(s) ____
8. ARRANGEMENT OF VIEWS. 37 CFR 1.84(i)
   ____ Words do not appear on a horizontal, left-to-right fashion when page is either upright or turned so that the top becomes the right side, except for graphs. Fig(s) ____
9. SCALE. 37 CFR 1.84(k)
   ____ Scale not large enough to show mechanism without crowding when drawing is reduced in size to two-thirds in reproduction.
   Fig(s) ____
10. CHARACTER OF LINES, NUMBERS, & LETTERS. 37 CFR 1.84(l)
    X Lines, numbers & letters not uniformly thick and well defined, clean, durable, and black (poor line quality).
    Fig(s) 1-17
11. SHADING. 37 CFR 1.84(m)
    ____ Solid black areas pale. Fig(s) ____
    ____ Solid black shading not permitted. Fig(s) ____
    ____ Shade lines, pale, rough and blurred. Fig(s) ____
12. NUMBERS, LETTERS, & REFERENCE CHARACTERS. 37 CFR 1.84(p)
    ____ Numbers and reference characters not plain and legible.
    Fig(s) ____
    ____ Figure legends are poor. Fig(s) ____
    ____ Numbers and reference characters not oriented in the same direction as the view. 37 CFR 1.84(p)(1)
    Fig(s) ____
    ____ English alphabet not used. 37 CFR 1.84(p)(2)
    Figs ____
    X Numbers, letters and reference characters must be at least .32 cm (1/8 inch) in height. 37 CFR 1.84(p)(3)
    Fig(s) ____
13. LEAD LINES. 37 CFR 1.84(q)
    ____ Lead lines cross each other. Fig(s) ____
    ____ Lead lines missing. Fig(s) ____
14. NUMBERING OF SHEETS OF DRAWINGS. 37 CFR 1.84(t)
    ____ Sheets not numbered consecutively, and in Arabic numerals beginning with number 1. Sheet(s) ____
15. NUMBERING OF VIEWS. 37 CFR 1.84(u)
    ____ Views not numbered consecutively, and in Arabic numerals, beginning with number 1. Fig(s) ____
16. CORRECTIONS. 37 CFR 1.84(w)
    ____ Corrections not made from prior PTO-948 dated ____
17. DESIGN DRAWINGS. 37 CFR 1.152
    ____ Surface shading shown not appropriate. Fig(s) ____
    ____ Solid black shading not used for color contrast.
    Fig(s) ____

COMMENTS Remove border lines fig. 3

REVIEWER [signature] DATE 3/8/00 TELEPHONE NO. ____

ATTACHMENT TO PAPER NO. 8

BEST COPY

UNITED STATES DEPARTMENT OF COMMERCE
Patent and Trademark Office

NOTICE OF ALLOWANCE AND ISSUE FEE DUE

QM12/0309

DAVID L FEIGENBAUM
FISH & RICHARDSON
225 FRANKLIN STREET
BOSTON MA 02110-2804

APPLICATION NO.	FILING DATE	TOTAL CLAIMS	EXAMINER AND GROUP ART UNIT		DATE MAILED
09/062,442	04/17/98	047	MARMOR II, C	3736	03/09/00

First Named Applicant: FOXLIN, 35 USC 154(b) term ext. = 0 Days.

TITLE OF INVENTION: MOTION TRACKING SYSTEM

ATTY'S DOCKET NO.	CLASS-SUBCLASS	BATCH NO.	APPLN. TYPE	SMALL ENTITY	FEE DUE	DATE DUE
09970002001	600-595.000	J33	UTILITY	NO	$1210.00	06/09/00

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED.

THE ISSUE FEE MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED.

HOW TO RESPOND TO THIS NOTICE:

I. Review the SMALL ENTITY status shown above.
If the SMALL ENTITY is shown as YES, verify your current SMALL ENTITY status:

A. If the status is changed, pay twice the amount of the FEE DUE shown above and notify the Patent and Trademark Office of the change in status, or
B. If the status is the same, pay the FEE DUE shown above.

If the SMALL ENTITY is shown as NO:

A. Pay FEE DUE shown above, or

B. File verified statement of Small Entity Status before, or with, payment of 1/2 the FEE DUE shown above.

II. Part B-Issue Fee Transmittal should be completed and returned to the Patent and Trademark Office (PTO) with your ISSUE FEE. Even if the ISSUE FEE has already been paid by charge to deposit account, Part B Issue Fee Transmittal should be completed and returned. If you are charging the ISSUE FEE to your deposit account, section "4b" of Part B-Issue Fee Transmittal should be completed and an extra copy of the form should be submitted.

III. All communications regarding this application must give application number and batch number.
Please direct all communications prior to issuance to Box ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.

PATENT AND TRADEMARK OFFICE COPY

#9

Attorney's Docket No.: 01997-238001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric M. Foxlin
Serial No. : 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit : 3736
Examiner : C. Marmor II
Notice of Allowance Date: March 3, 2000

OIPE JC72 JUN 1 3 2000 PATENT & TRADEMARK OFFICE

BOX ISSUE FEE
Commissioner for Patents
Washington, D.C. 20231

RESPONSE TO NOTICE OF ALLOWANCE

In response to the Notice of Allowance mailed March 9, 2000, enclosed are a completed issue fee transmittal form PTOL-85b, transmittal of 16 sheets of formal drawings, and a check for $1240 for the required fee, including patent copies.

Please apply any charges or credits to our Deposit Account No. 06-1050.

Respectfully submitted,

Date: 6/9/00

Lawrence K. Kolodney
Reg. No. 43,807

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804
Telephone: (617) 542-5070
Facsimile: (617) 542-8906

20060158.doc

CERTIFICATE OF MAILING BY FIRST CLASS MAIL

I hereby certify under 37 CFR §1.8(a) that this correspondence is being deposited with the United States Postal Service as first class mail with sufficient postage on the date indicated below and is addressed to the Commissioner for Patents, Washington, D.C. 20231.

June 9, 2000
Date of Deposit

Signature

Christine Powers
Typed or Printed Name of Person Signing Certificate

PART B—ISSUE FEE TRANSMITTAL

B 8

Complete and mail this form, together with applicable fees, to: **Box ISSUE FEE**
Assistant Commissioner for Patents
Washington, D.C. 20231

MAILING INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE. Blocks 1 through 4 should be completed where appropriate. All further correspondence including the Issue Fee Receipt, the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Legibly mark-up with any corrections or use Block 1)

DM12/0309

DAVID L FEIGENBAUM
FISH & RICHARDSON
225 FRANKLIN STREET
BOSTON MA 02110-2804

OIPE
JUN 13 2000
PATENT & TRADEMARK OFFICE
JC7

Note: The certificate of mailing below can only be used for domestic mailings of the Issue Fee Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing.

Certificate of Mailing

I hereby certify that this Issue Fee Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Box Issue Fee address above on the date indicated below.

Christine Powers (Depositor's name)
Christine Powers (Signature)
June 9, 2000 (Date)

APPLICATION NO.	FILING DATE	TOTAL CLAIMS	EXAMINER AND GROUP ART UNIT		DATE MAILED
09/062,442	04/17/98	047	MARMOR II, C	3736	03/09/0

First Named Applicant: FOXLIN, 35 USC 154(b) term ext. = 0 Days.

TITLE OF INVENTION: MOTION TRACKING SYSTEM

ATTY'S DOCKET NO.	CLASS-SUBCLASS	BATCH NO.	APPLN. TYPE	SMALL ENTITY	FEE DUE	DATE DUE
3 09970002001	600-395.000	J33	UTILITY	NO	$1210.00	06/09/

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363). Use of PTO form(s) and Customer Number are recommended, but not required.

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47) attached.

2. For printing on the patent front page, list (1) the names of up to 3 registered patent attorneys or agents OR, alternatively, (2) the name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 Fish & Richardson P.C.
2 ________
3 ________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)
PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. Inclusion of assignee data is only appropriate when an assignment has been previously submitted to the PTO or is being submitted under separate cover. Completion of this form is NOT a subsititue for filing an assignment.

(A) NAME OF ASSIGNEE
Massachusetts Institute of Technology
(B) RESIDENCE: (CITY & STATE OR COUNTRY)
Cambridge, Massachusetts

Please check the appropriate assignee category indicated below (will not be printed on the patent)
☐ individual ☒ corporation or other private group entity ☐ government

4a. The following fees are enclosed (make check payable to Commissioner of Patents and Trademarks):
☒ Issue Fee
☒ Advance Order - # of Copies 10

4b. The following fees or deficiency in these fees should be charged to:
DEPOSIT ACCOUNT NUMBER 06-1050
(ENCLOSE AN EXTRA COPY OF THIS FORM)
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☐ Advance Order - # of Copies ______

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PTOL-85B (REV.10-96) Approved for use through 06/30/99. OMB 0651-0033

Patent and Trademark Office; U.S. DEPARTMENT OF COMME

6176837

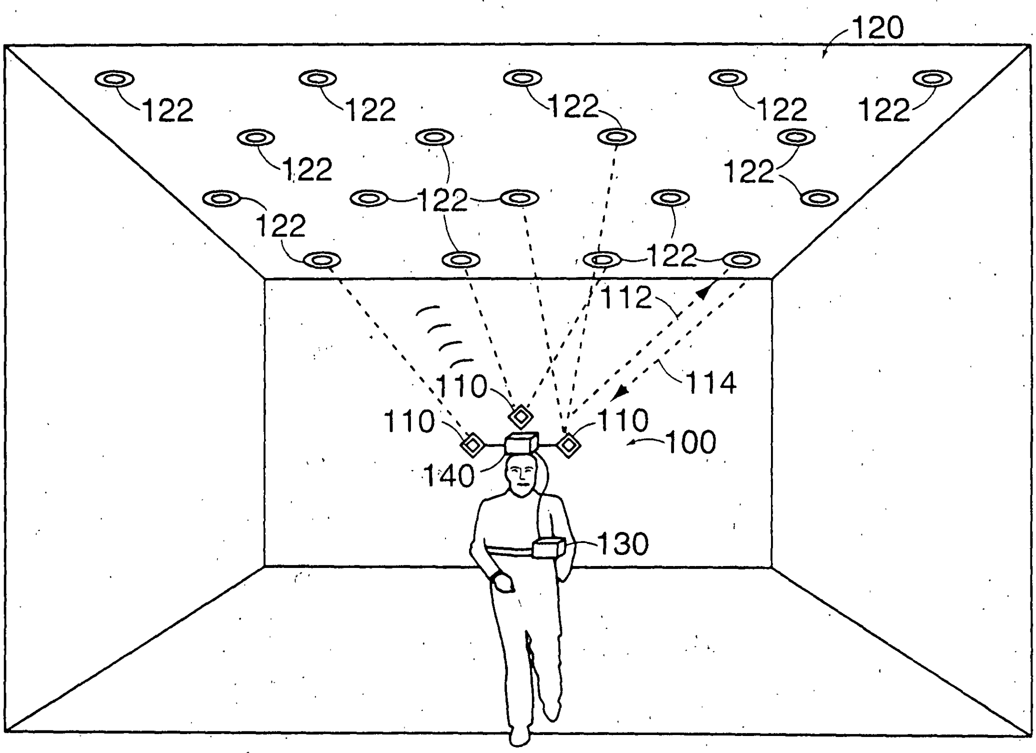


FIG. 1

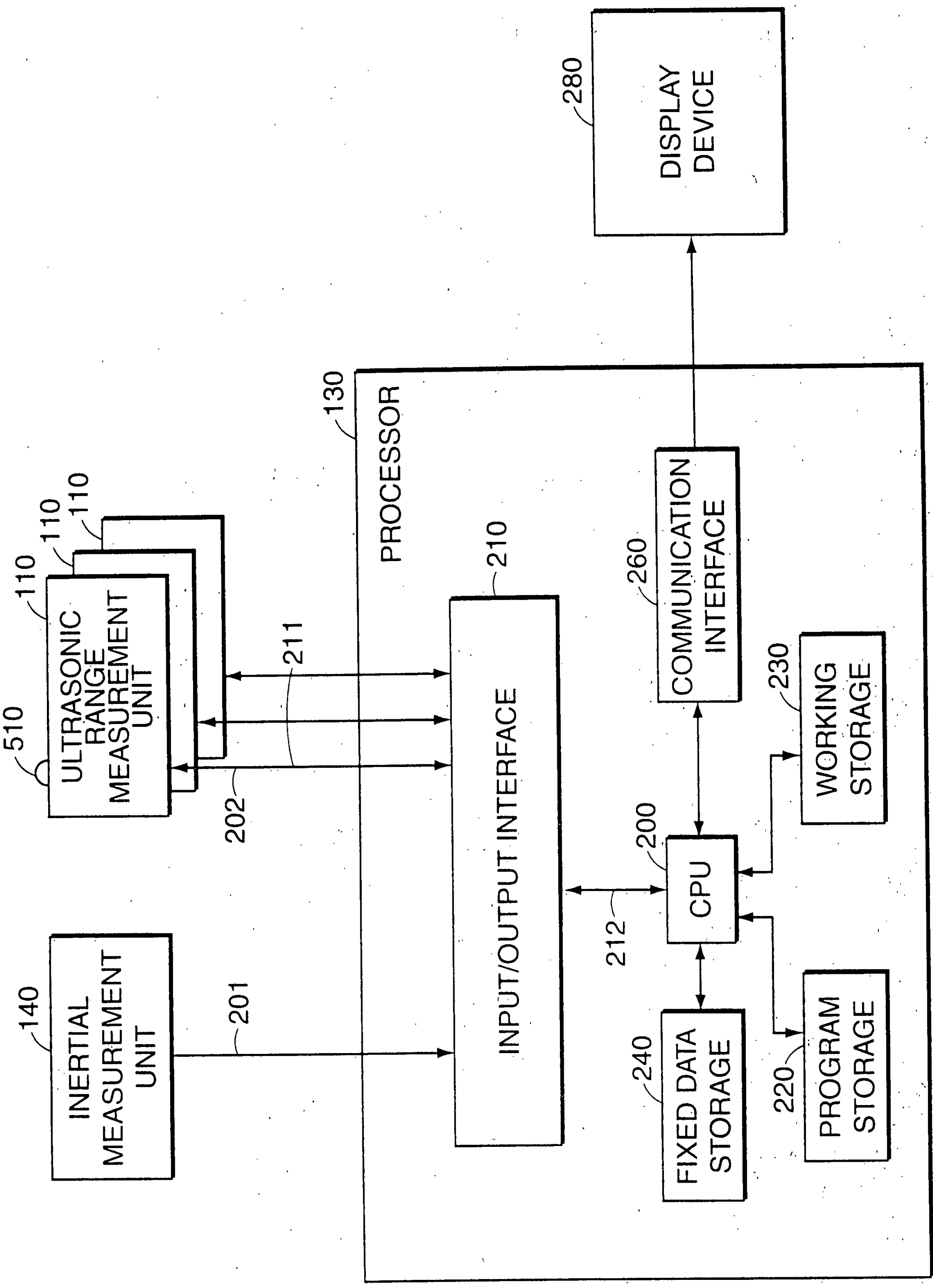

110
110
110
ULTRASONIC RANGE MEASUREMENT UNIT
510
211
202
140
INERTIAL MEASUREMENT UNIT
201
130
PROCESSOR
210
INPUT/OUTPUT INTERFACE
212
200
CPU
260
COMMUNICATION INTERFACE
230
WORKING STORAGE
220
PROGRAM STORAGE
240
FIXED DATA STORAGE
280
DISPLAY DEVICE

FIG. 2

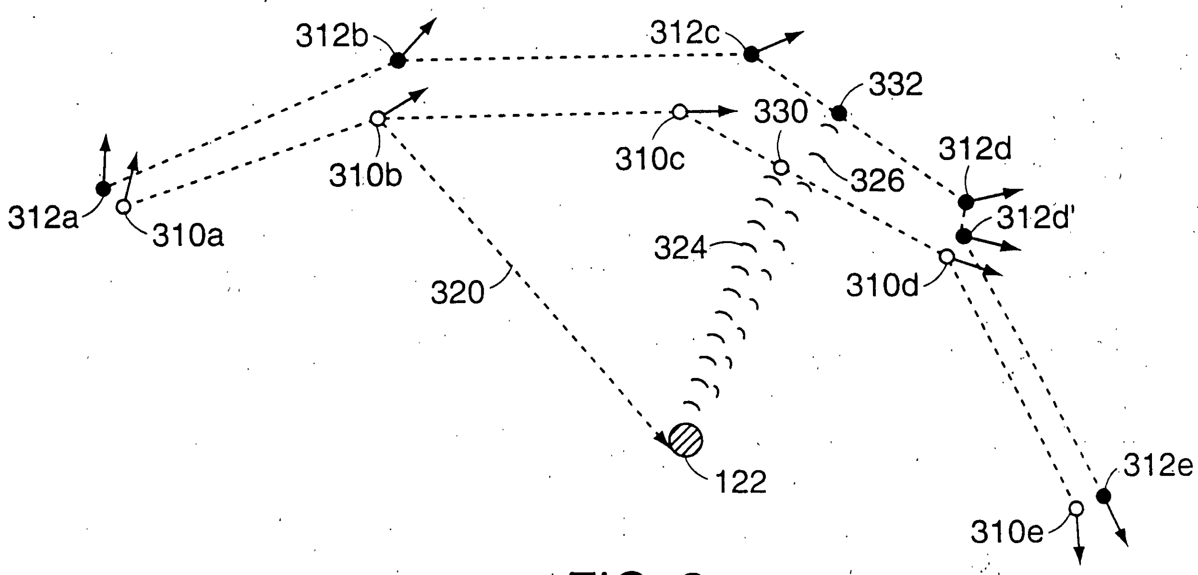
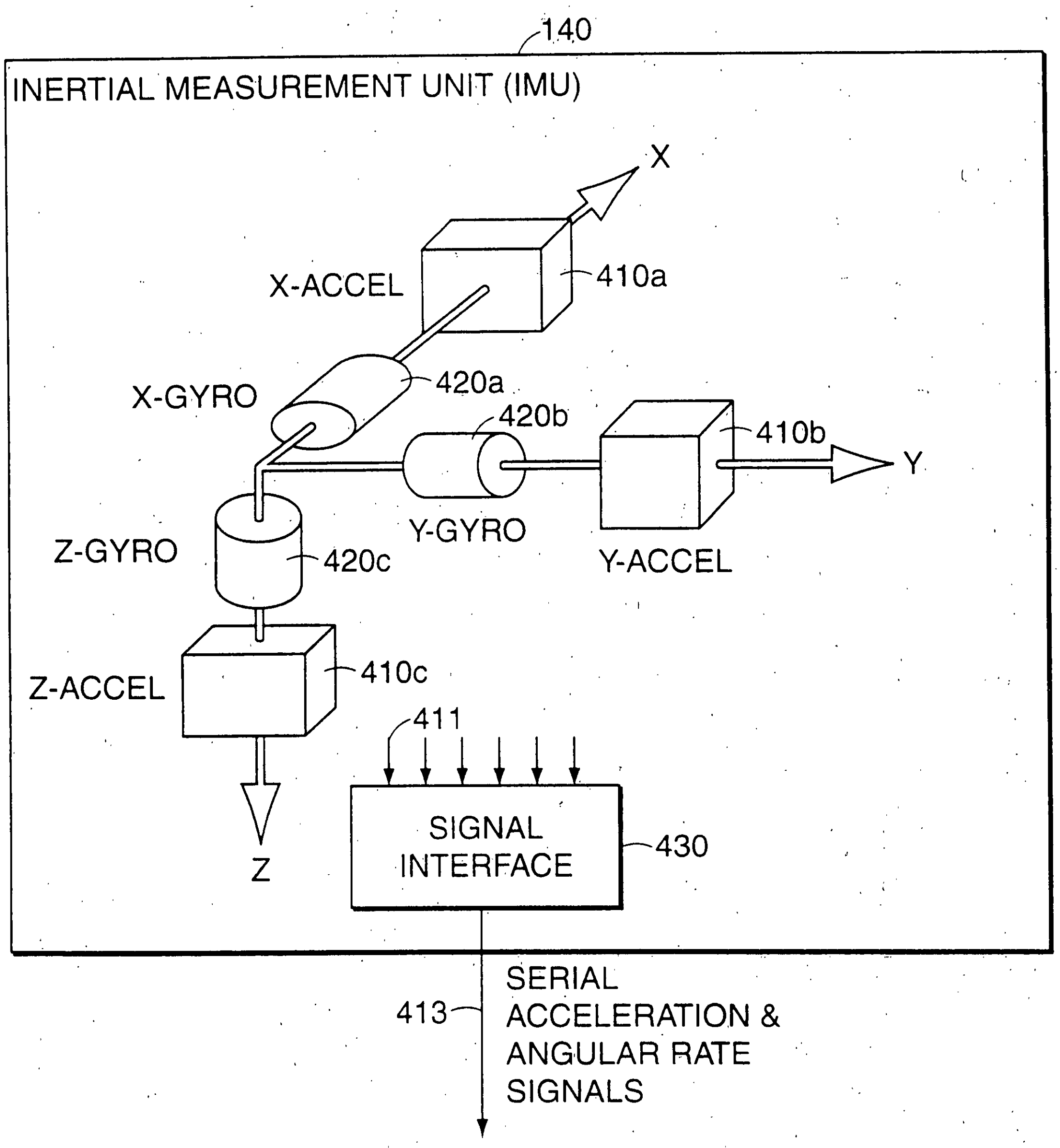

312b
312c
332
330
310b
310c
326
312d
312d'
312a
310a
324
310d
320
122
312e
310e

FIG. 3



140
INERTIAL MEASUREMENT UNIT (IMU)
X
X-ACCEL
410a
X-GYRO
420a
420b
410b
Y
Z-GYRO
420c
Y-GYRO
Y-ACCEL
Z-ACCEL
410c
411
SIGNAL
INTERFACE
430
Z
413
SERIAL
ACCELERATION &
ANGULAR RATE
SIGNALS

FIG. 4

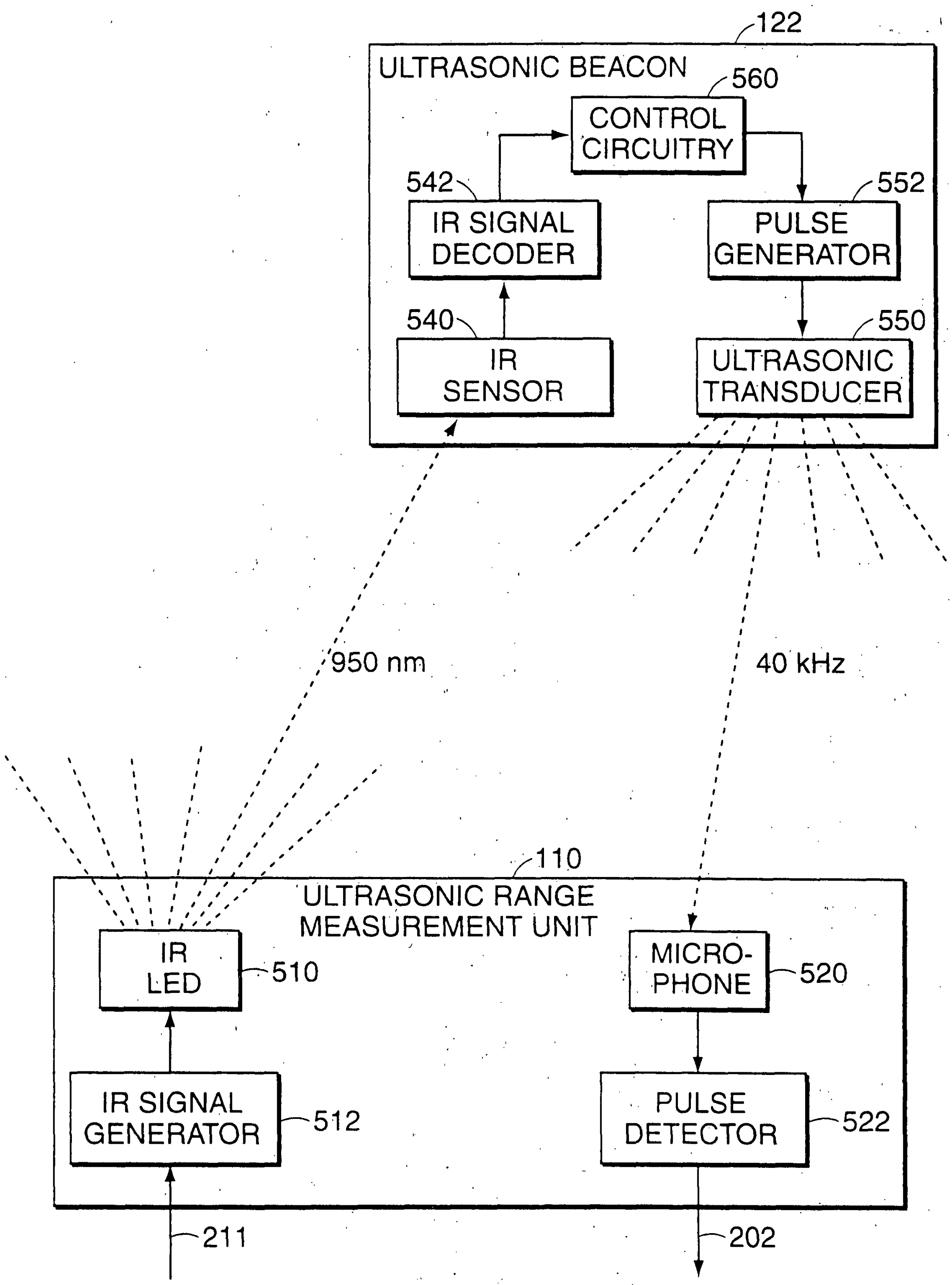
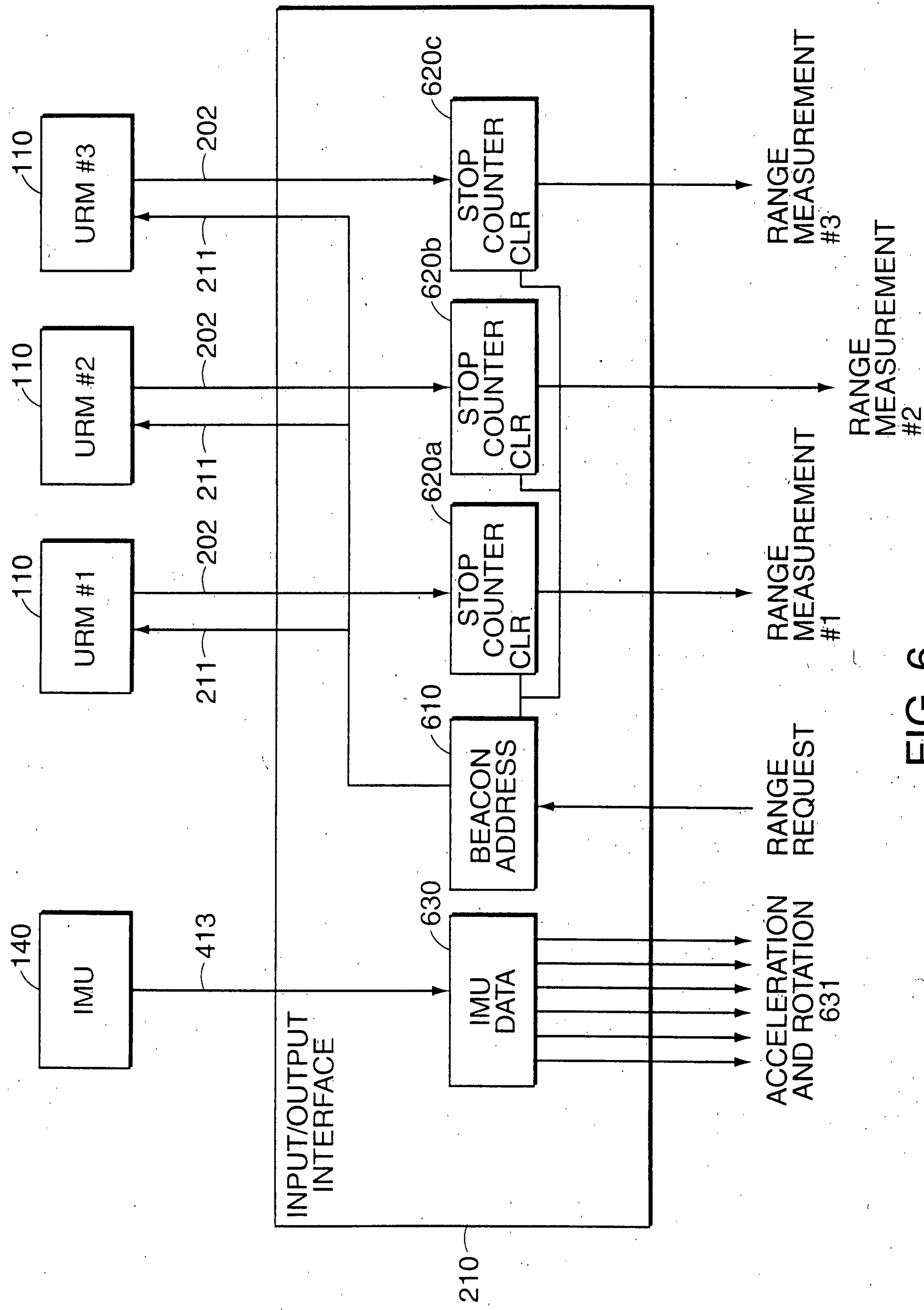
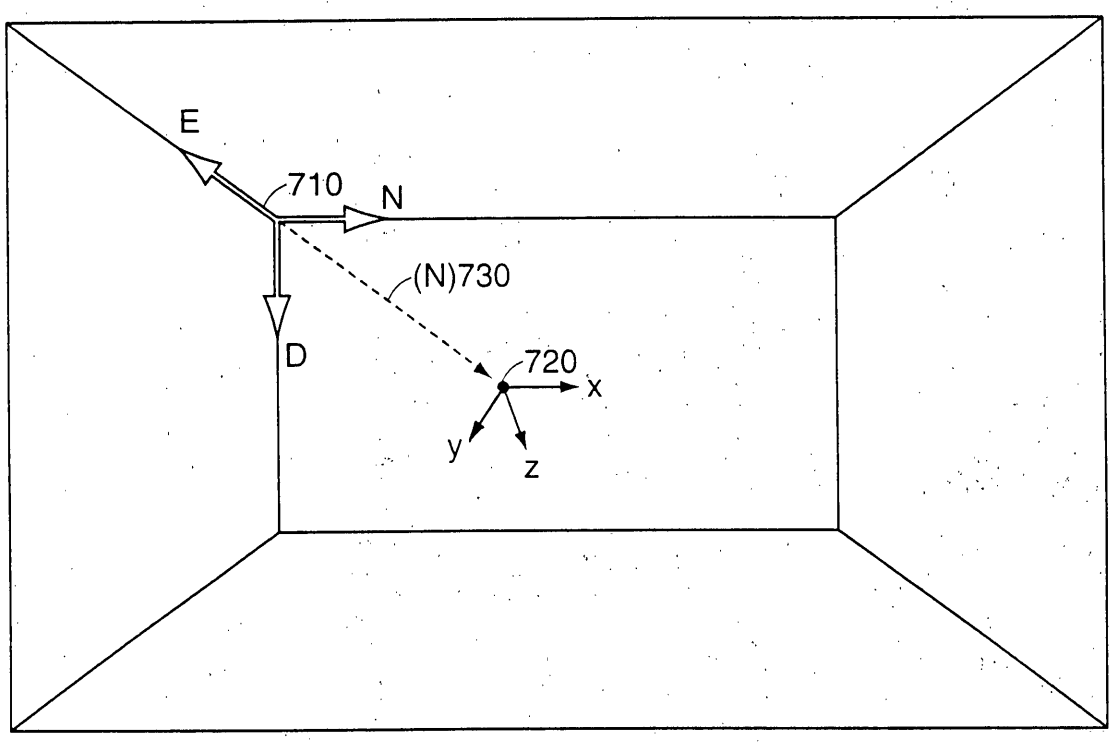

122
ULTRASONIC BEACON
560
CONTROL CIRCUITRY
542
IR SIGNAL DECODER
552
PULSE GENERATOR
540
IR SENSOR
550
ULTRASONIC TRANSDUCER
950 nm
40 kHz
110
ULTRASONIC RANGE MEASUREMENT UNIT
IR LED
510
MICRO-PHONE
520
IR SIGNAL GENERATOR
512
PULSE DETECTOR
522
211
202

FIG. 5



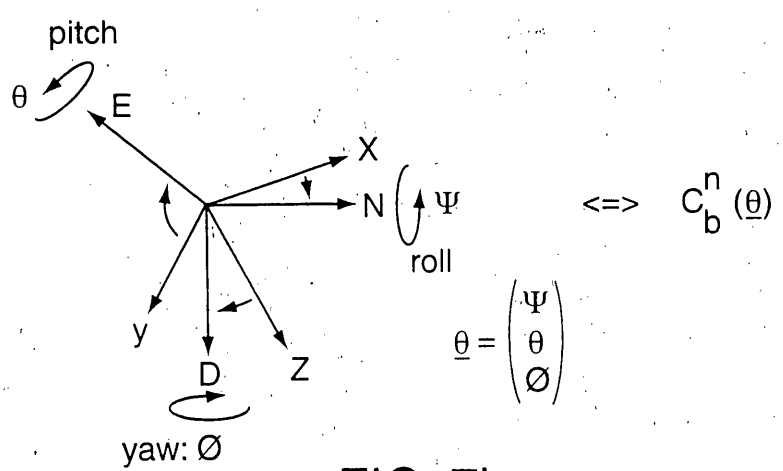
110
URM #3
110
URM #2
110
URM #1
140
IMU
202
211
413
INPUT/OUTPUT INTERFACE
210
620c
620b
620a
610
630
STOP COUNTER CLR
BEACON ADDRESS
IMU DATA
RANGE MEASUREMENT #3
RANGE MEASUREMENT #2
RANGE MEASUREMENT #1
RANGE REQUEST
ACCELERATION AND ROTATION 631

FIG. 6



E
710
N
(N)730
D
720
x
y
z

FIG. 7a



pitch
θ
E
X
N
Ψ
roll
<=>
$C_b^n(\underline{\theta})$
y
D
Z
yaw: Ø
$\underline{\theta} = \begin{pmatrix} \Psi \\ \theta \\ Ø \end{pmatrix}$

FIG. 7b

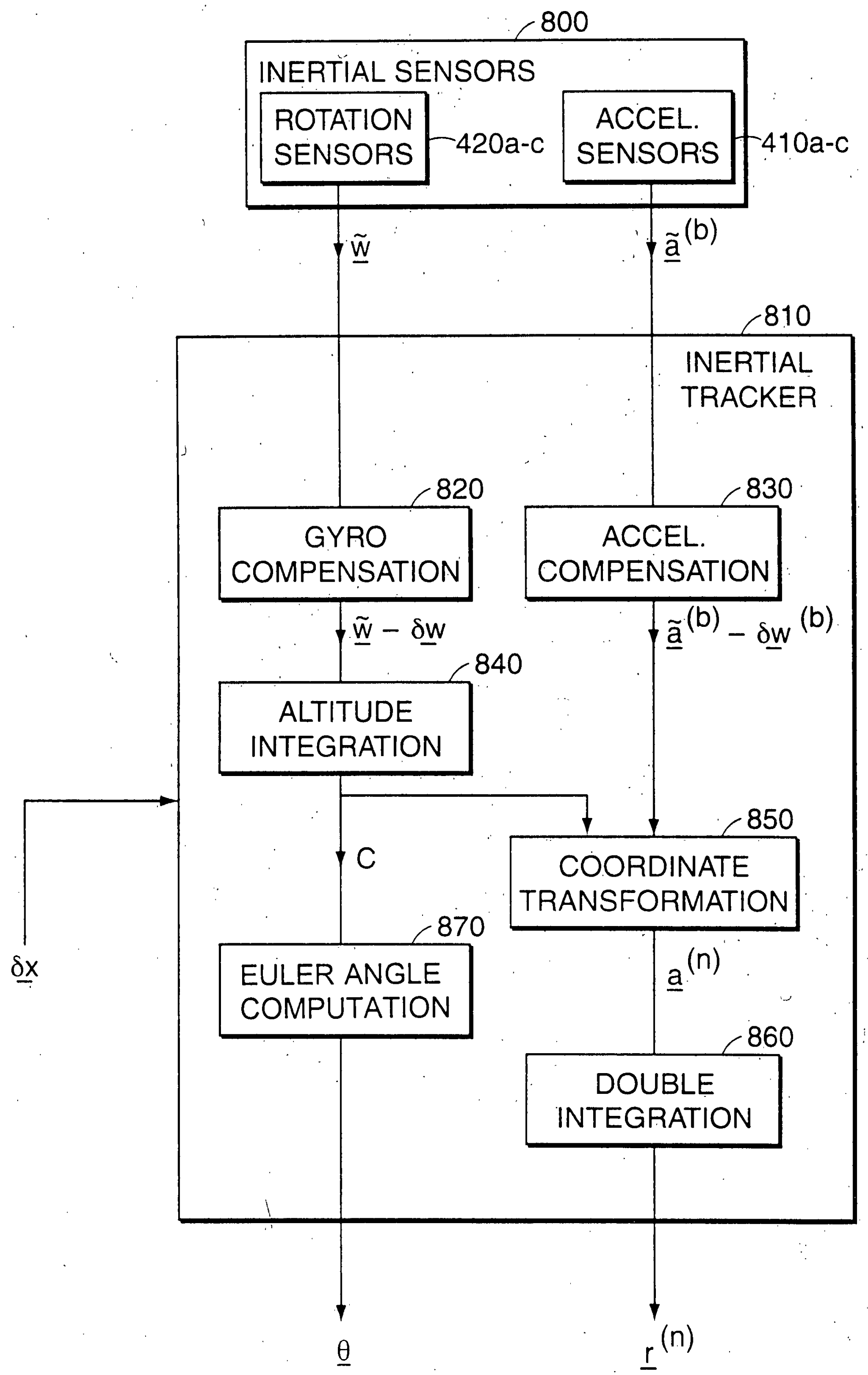

800
INERTIAL SENSORS
ROTATION SENSORS
420a-c
ACCEL. SENSORS
410a-c
w̃
ã(b)
810
INERTIAL TRACKER
820
GYRO COMPENSATION
830
ACCEL. COMPENSATION
w̃ − δw
ã(b) − δw (b)
840
ALTITUDE INTEGRATION
850
COORDINATE TRANSFORMATION
C
δx
870
EULER ANGLE COMPUTATION
a(n)
860
DOUBLE INTEGRATION
θ
r(n)

FIG. 8

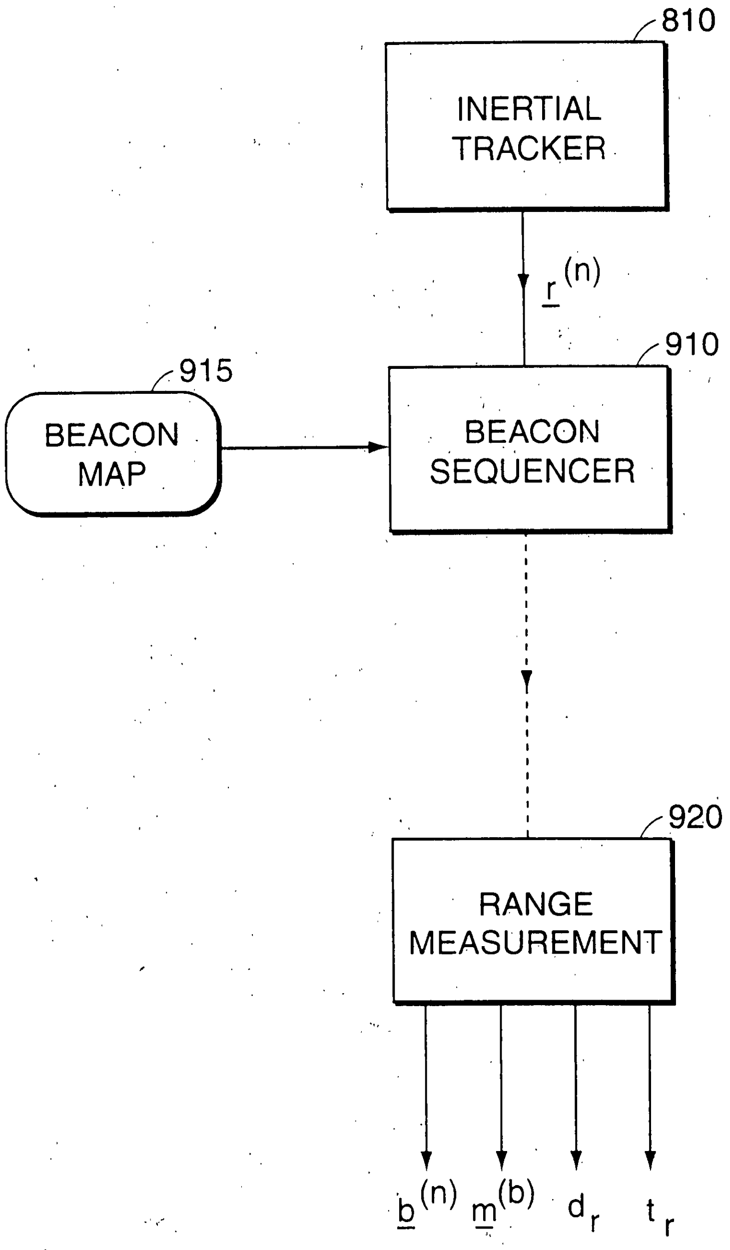

810
INERTIAL
TRACKER
r (n)
910
915
BEACON
MAP
BEACON
SEQUENCER
920
RANGE
MEASUREMENT
b (n)
m (b)
d r
t r

FIG. 9

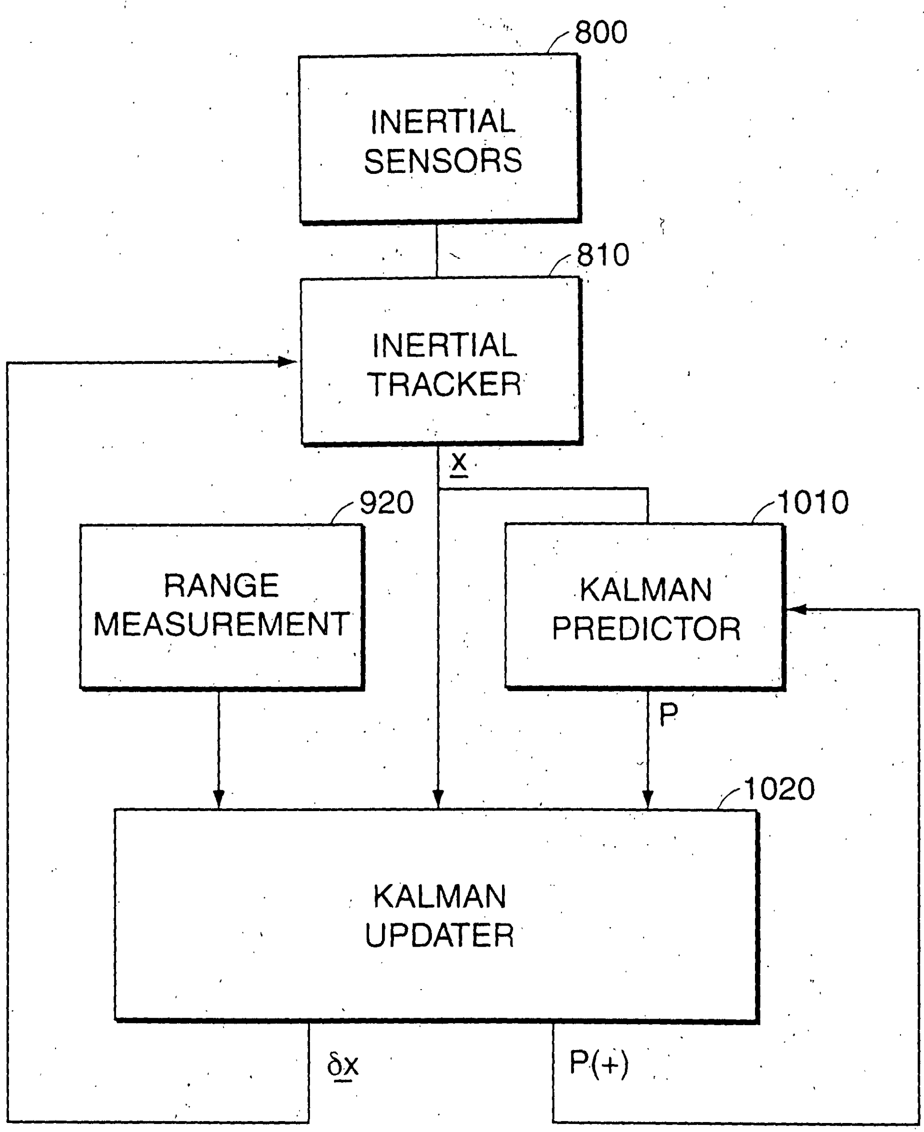

800
INERTIAL SENSORS
810
INERTIAL TRACKER
x
920
RANGE MEASUREMENT
1010
KALMAN PREDICTOR
P
1020
KALMAN UPDATER
δx
P(+)

FIG. 10

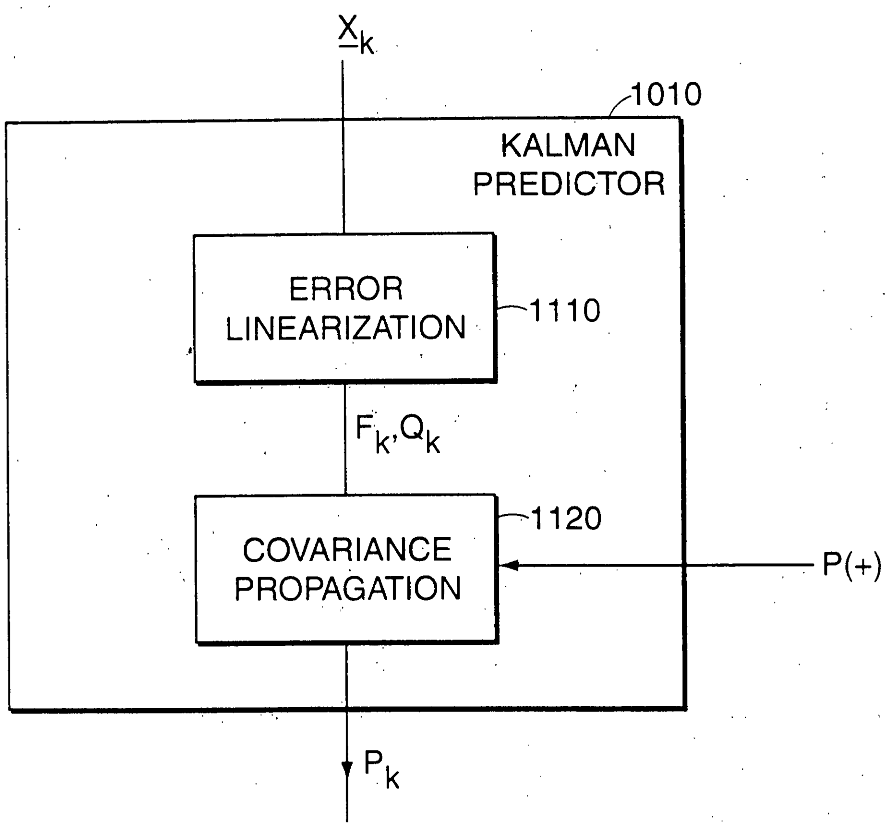

$\underline{X}_k$
1010
KALMAN PREDICTOR
ERROR LINEARIZATION
1110
F_k, Q_k
1120
COVARIANCE PROPAGATION
P(+)
P_k

FIG. 11

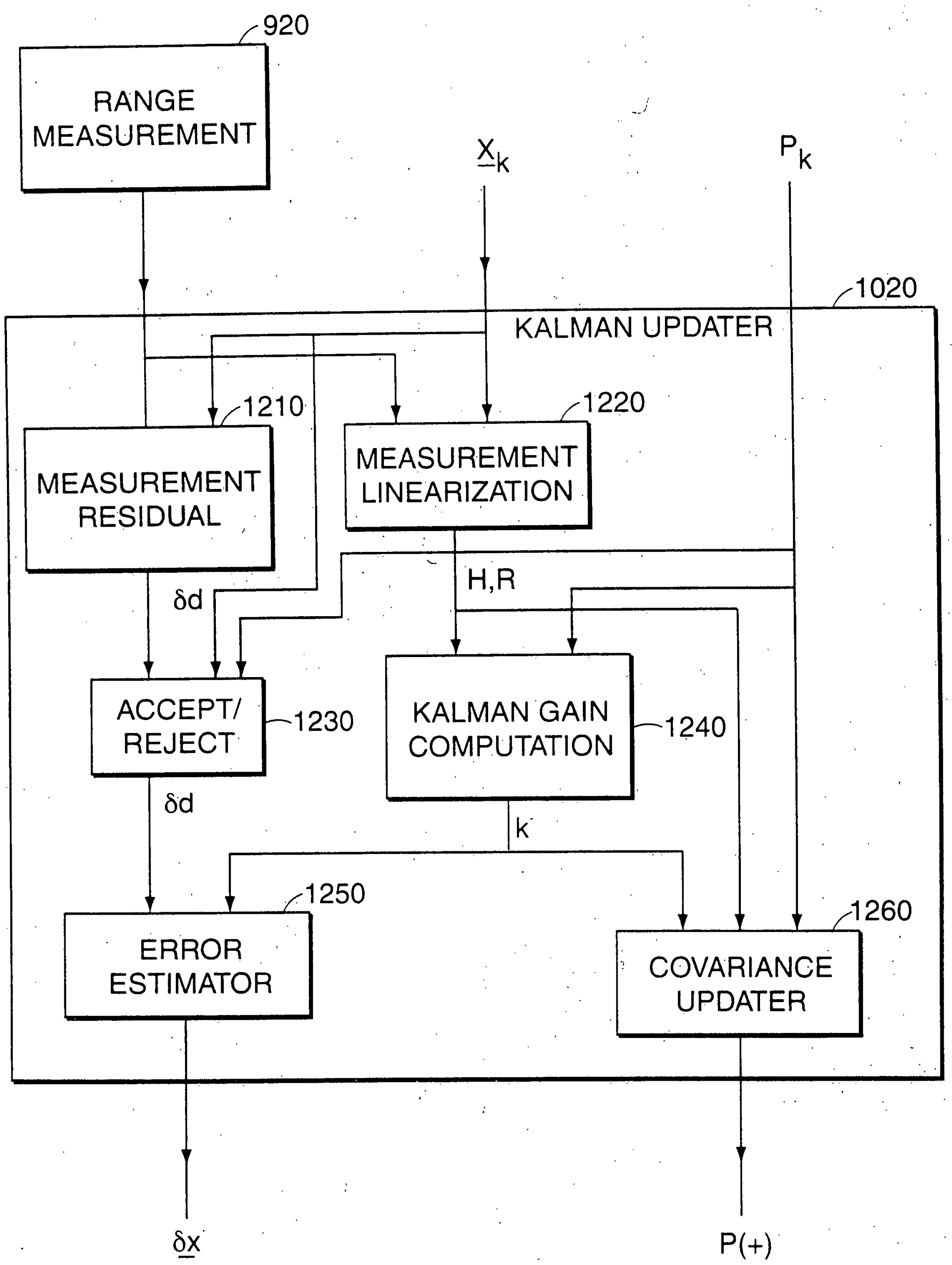

920
RANGE MEASUREMENT
$\underline{X}_k$
P_k
1020
KALMAN UPDATER
1210
MEASUREMENT RESIDUAL
1220
MEASUREMENT LINEARIZATION
H,R
δd
ACCEPT/ REJECT
1230
KALMAN GAIN COMPUTATION
1240
δd
k
1250
ERROR ESTIMATOR
1260
COVARIANCE UPDATER
$\delta\underline{x}$
P(+)

FIG. 12

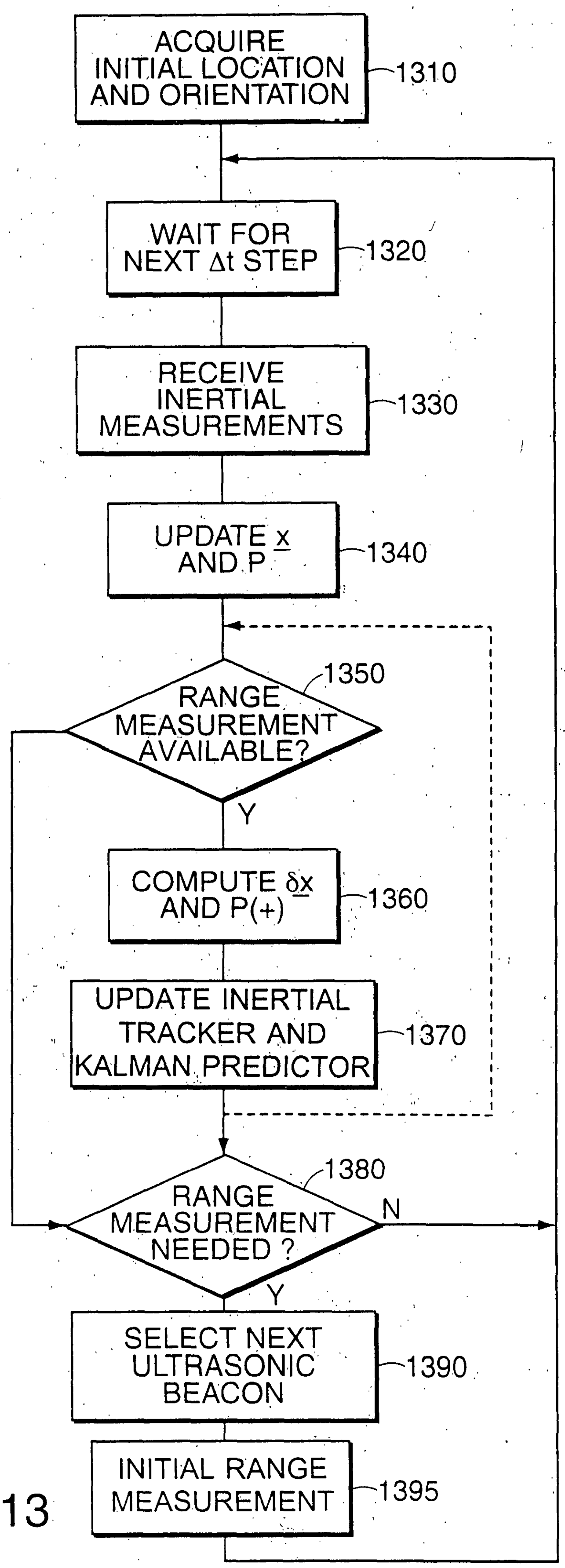

ACQUIRE INITIAL LOCATION AND ORIENTATION
1310
WAIT FOR NEXT Δt STEP
1320
RECEIVE INERTIAL MEASUREMENTS
1330
UPDATE x AND P
1340
RANGE MEASUREMENT AVAILABLE?
1350
Y
COMPUTE δx AND P(+)
1360
UPDATE INERTIAL TRACKER AND KALMAN PREDICTOR
1370
RANGE MEASUREMENT NEEDED ?
1380
N
Y
SELECT NEXT ULTRASONIC BEACON
1390
INITIAL RANGE MEASUREMENT
1395

FIG. 13

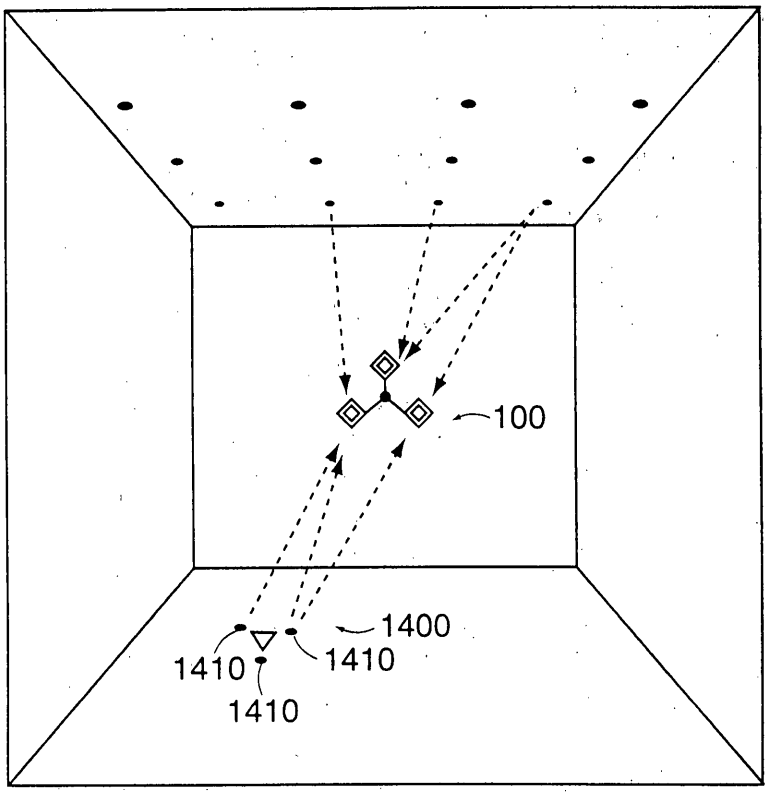


FIG. 14a

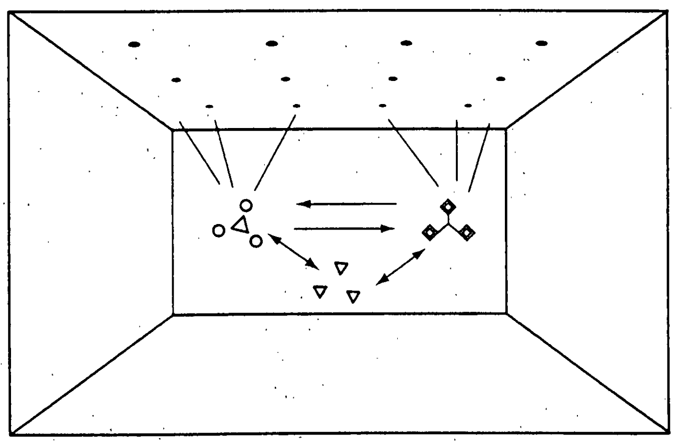


FIG. 14b

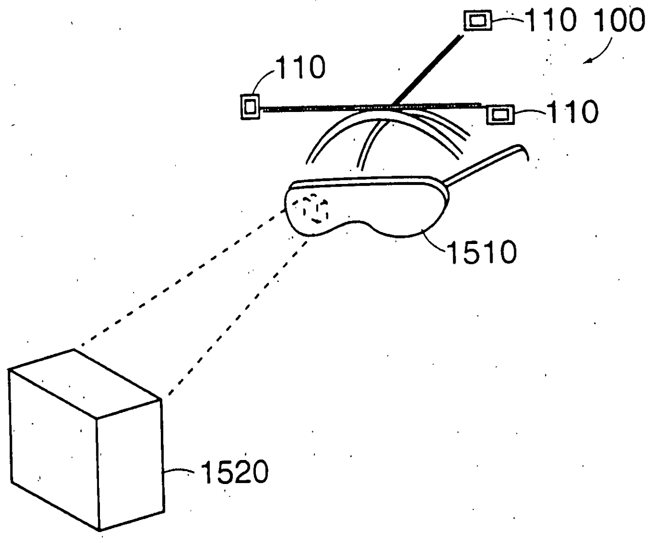


FIG. 15

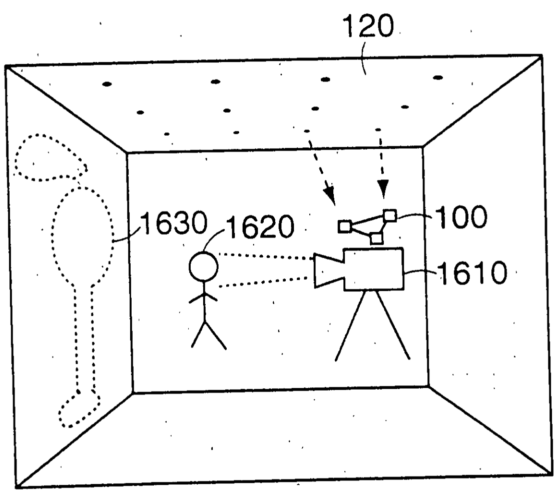


FIG. 16

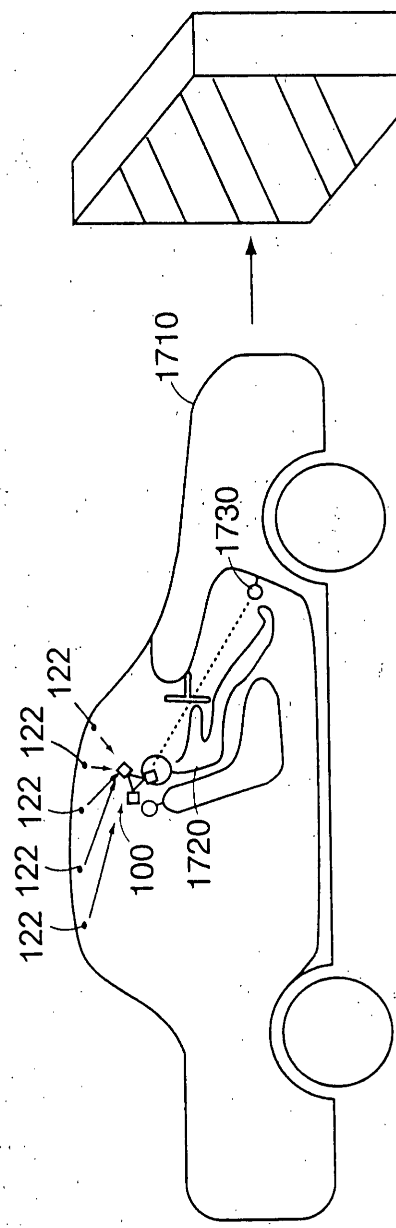


FIG. 17

Sheet 16 of 16 Sheets

Applicant: Eric M. Foxlin
Title: MOTION TRACKING SYSTEM
Serial No.: 09/062,442
Attorney/Agent: David L. Feigenbaum, Reg. No. 30,378
Docket No.: 01997-238001
Notice of Allowance Mailed: March 9, 2000

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804

Copy

Attorney's Docket No.: 01997-238001 / MIT Case 8226S

RTC

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

#10
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Applicant : Eric Foxlin
Patent No. : 6,176,837
Issue Date : January 23, 2001
Serial No. : 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit : Unknown
Examiner : Unknown

Commissioner for Patents
Washington, D.C. 20231

TRANSMITTAL OF REQUEST FOR CERTIFICATE OF CORRECTION

Applicant hereby requests that a certificate of correction be issued for the above patent in accordance with the attached request.

All errors sought to be corrected were made in printing by the Patent and Trademark Office and no fee is believed to be due.

Please apply any charges or credits to Deposit Account No. 06-1050.

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FOR THE DIRECTOR OF USPTO

Respectfully submitted,

Date: December 10, 2001

Eric L. Prahl
Reg. No. 32,590

CERTIFICATE
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OF CORRECTION

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JAN 0 8 2002
PATENT & TRADEMARK OFFICE

Attorney's Docket No.: 01997-238001 / MIT Case 8226S

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant : Eric Foxlin
Patent No. : 6,176,837
Issue Date : January 23, 2001
Serial No. : 09/062,442
Filed : April 17, 1998
Title : MOTION TRACKING SYSTEM

Art Unit : Unknown
Examiner : Unknown

Commissioner for Patents
Washington, D.C. 20231

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Please apply any charges or credits to Deposit Account No. 06-1050.

Respectfully submitted,

Date: December 10, 2001

Eric L. Prahl
Reg. No. 32,590

Fish & Richardson P.C.
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Boston, Massachusetts 02110-2804
Telephone: (617) 542-5070
Facsimile: (617) 542-8906

20353493.doc

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December 10, 2001
Date of Deposit

Signature

Vasilia Kelly
Typed or Printed Name of Person Signing Certificate

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,176,837 B1

DATED : JANUARY 23, 2001

INVENTOR(S) : ERIC FOXLIN

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 16, l. 38, delete "determining a range measurement based on a time of flight of the range measurement signal" and insert -- obtaining an inertial measurement; and updating the location estimate or orientation estimate based on the inertial measurement --.

Col. 16, l. 40, "10" should be -- 9 --.

MAILING ADDRESS OF SENDER:

Eric L. Prahl
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PATENT NO. 6,176,837

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UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,176,837
DATED : JANUARY 23, 2001
INVENTOR(S) : ERIC FOXLIN

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

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Col. 16, l. 40, "10" should be -- 9 --.

MAILING ADDRESS OF SENDER:

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PATENT NO. 6,176,837
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DATE : 04/25/02 **Paper No.:** 11

TO : **Supervisor, Art Unit** 3700

SUBJECT : **Certificate of Correction Request in Patent No.:** 6176837

A response to the following question is requested with respect to the accompanying request for a certif of correction.

With respect to the change(s) requested, correcting Office and/or Applicant's errors, should the patent read as shown in the certificate of correction? No new matter should be introduced, nor should scope or meaning of the claims be changed.

Yes

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PALM LOCATION 7580 - TEL. N0. 305-8309

THANK YOU FOR YOUR ASSISTANCE!

Note your decision, regarding the changes requested in the Request for Certificate of Correction, placing a check mark (+) in the box that reflects your decision, which corresponds to the question check above.

☒ **YES** ☐ **NO** ☐ **Comments below**

☐ **Comments:**

Supervisor **Art Unit** 3736

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,176,837 B1
DATED : January 23, 2001
INVENTOR(S) : Eric Foxlin

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 16,
Line 38, delete "determining a range measurement based on a time of flight of the range measurement signal" and insert -- obtaining an inertial measurement; and updating the location estimate or orientation estimate based on the inertial measurement --.
Line 40, "10" should be -- 9 --.

Signed and Sealed this

Eighteenth Day of June, 2002

Attest:

Attesting Officer

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

PATENT APPLICATION FEE DETERMINATION RECORD

Effective October 1, 1997

Application or Docket Number: 09/662442

CLAIMS AS FILED - PART I

FOR	NUMBER FILED (Column 1)		NUMBER EXTRA (Column 2)	SMALL ENTITY TYPE ☐ RATE	FEE	OR	OTHER THAN SMALL ENTITY RATE	FEE
BASIC FEE					395.00	OR		790.00
TOTAL CLAIMS	15	minus 20 =	* —	x$11=		OR	x$22=	—
INDEPENDENT CLAIMS	6	minus 3 =	* 3	x41=		OR	x82=	246
MULTIPLE DEPENDENT CLAIM PRESENT				+135=		OR	+270=	
				TOTAL		OR	TOTAL	1036

* If the difference in column 1 is less than zero, enter "0" in column 2

CLAIMS AS AMENDED - PART II

AMENDMENT A

	CLAIMS REMAINING AFTER AMENDMENT (Column 1)		HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2)	PRESENT EXTRA (Column 3)	SMALL ENTITY RATE	ADDITIONAL FEE	OR	OTHER THAN SMALL ENTITY RATE	ADDITIONAL FEE
Total	*	Minus	**	=	x$11=		OR	x$22=	
Independent	*	Minus	***	=	x41=		OR	x82=	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+135=		OR	+270=	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	

AMENDMENT B

	CLAIMS REMAINING AFTER AMENDMENT (Column 1)		HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2)	PRESENT EXTRA (Column 3)	RATE	ADDITIONAL FEE	OR	RATE	ADDITIONAL FEE
Total	*	Minus	**	=	x$11=		OR	x$22=	
Independent	*	Minus	***	=	x41=		OR	x82=	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+135=		OR	+270=	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	

AMENDMENT C

	CLAIMS REMAINING AFTER AMENDMENT (Column 1)		HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2)	PRESENT EXTRA (Column 3)	RATE	ADDITIONAL FEE	OR	RATE	ADDITIONAL FEE
Total	*	Minus	**	=	x$11=		OR	x$22=	
Independent	*	Minus	***	=	x41=		OR	x82=	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+135=		OR	+270=	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20."
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3."
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

US006176837B1

(12) **United States Patent**
Foxlin

(10) **Patent No.: US 6,176,837 B1**
(45) **Date of Patent: Jan. 23, 2001**

(54) **MOTION TRACKING SYSTEM**

(75) Inventor: **Eric M. Foxlin**, Arlington, MA (US)

(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(*) Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 0 days.

(21) Appl. No.: **09/062,442**

(22) Filed: **Apr. 17, 1998**

(51) **Int. Cl.**[7] **A61B 5/103**
(52) **U.S. Cl.** **600/595**; 600/587; 128/897
(58) **Field of Search** 600/587, 595; 364/478.01; 348/169; 367/117, 118; 128/898, 897; 73/488, 503.3, 504.03, 510, 514.01

(56) **References Cited**

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5,645,077	7/1997	Foxlin	128/774

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Hollands, "Sourcelss Trackers," Technology Review, 4(3):23–27, 1995.

Sowizral and Barnes, "Tracking Position and Orientation in a Large Volume," IEEE, pp. 132–139, 1993.

Angularis VR–360 Inertial Tracking System Brochure, Nov. 1995.

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Proposal for tracking system, Oct. 1996.

Intersense IS–600 Precision Motion Tracker Brochure, May 1997.

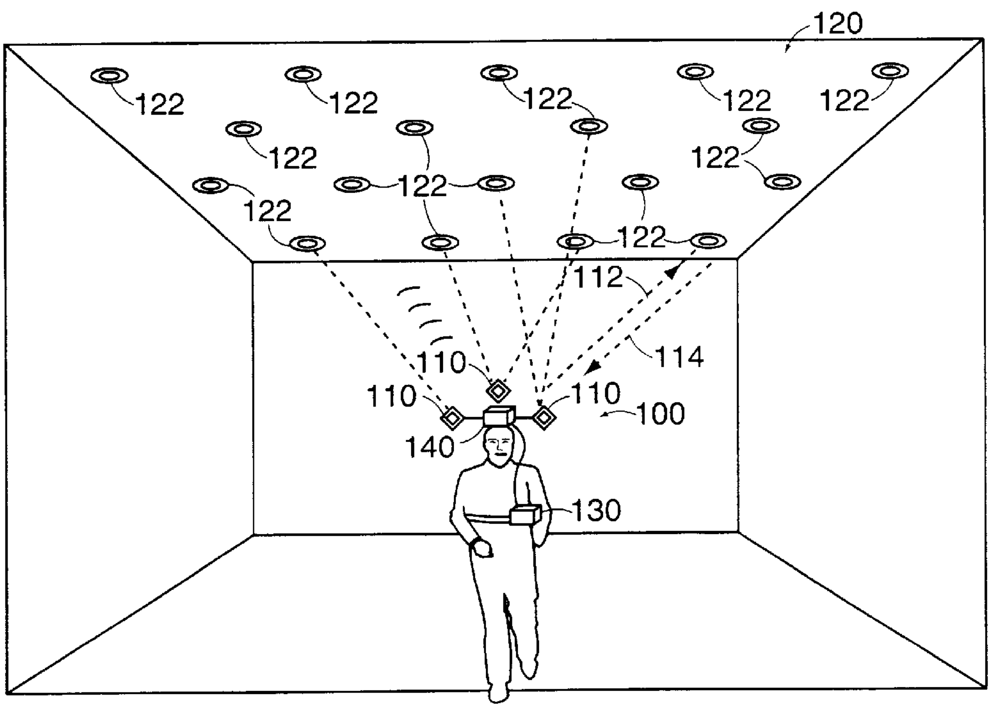
Intersense IS–900CT Camera Tracker Brochure, Jul. 1997.

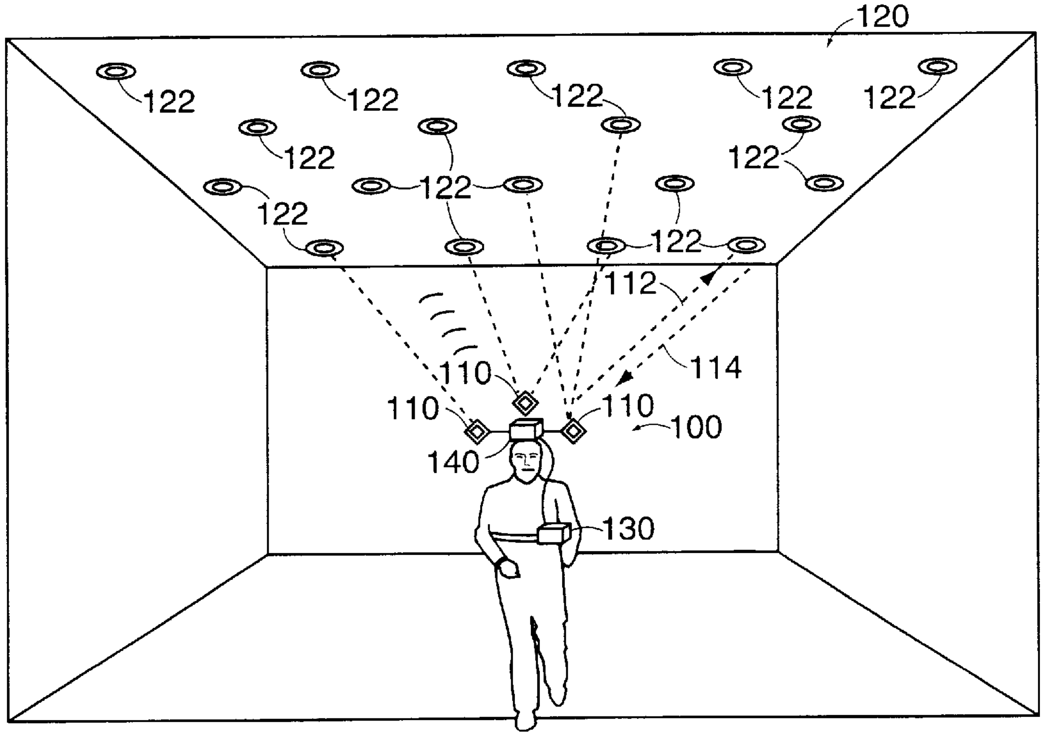
Primary Examiner—Cary O'Connor
Assistant Examiner—Charles Marmor, II
(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

Tracking a motion of a body by obtaining two types of measurements associated with the motion of the body, one of the types including acoustic measurement. An estimate of either an orientation or a position of the body is updated based on one of the two types of measurement, for example based on inertial measurement. The estimate is then updated based on the other of the two types of measurements, for example based on acoustic ranging. The invention also features determining range measurement to selected reference devices that are fixed in the environment of the body.

47 Claims, 16 Drawing Sheets




120
122
122
122
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122
122
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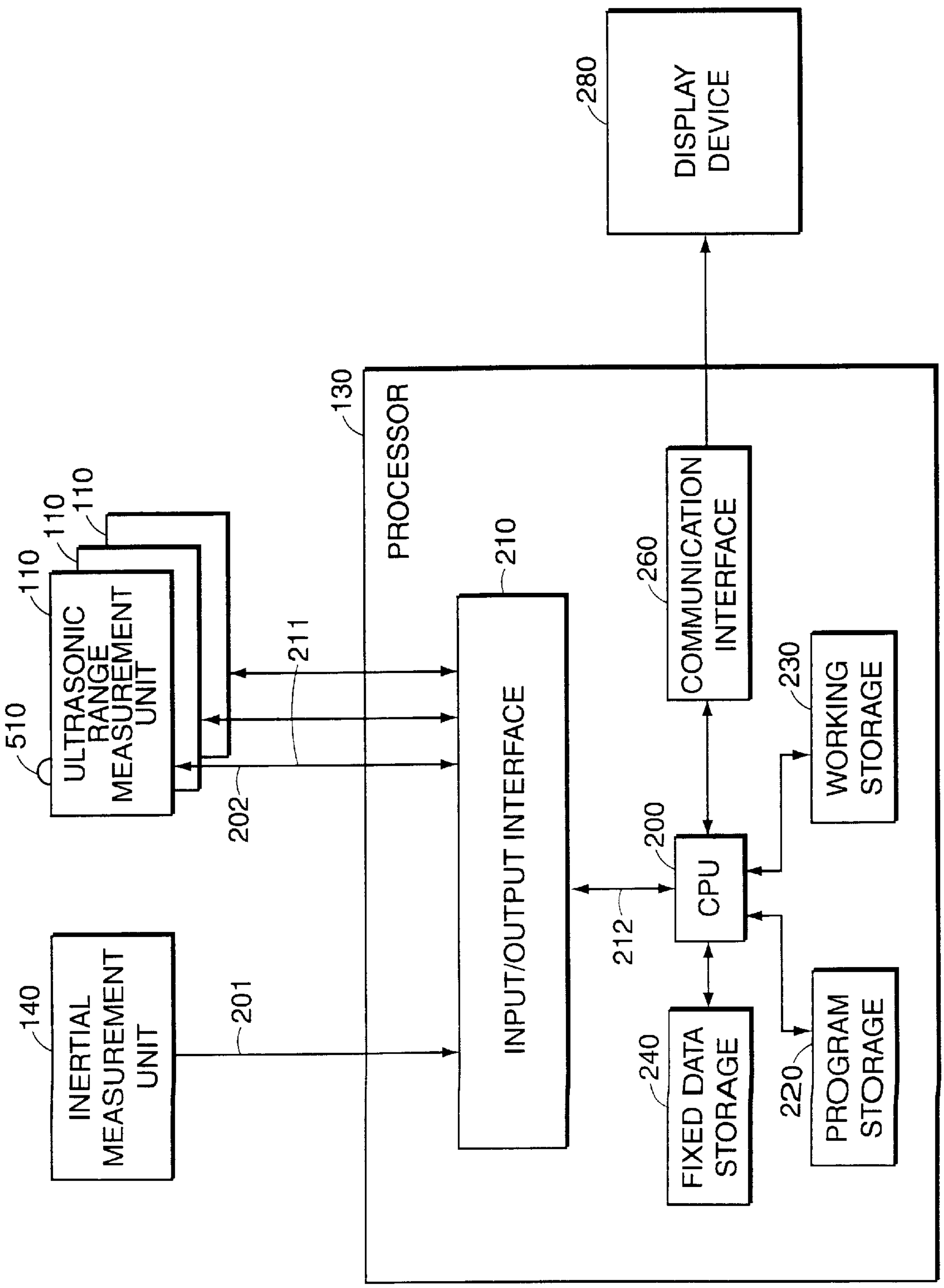
122
122
122
112
114
110
110
110
100
140
130

FIG. 1



280
DISPLAY DEVICE
130
PROCESSOR
110
110
110
510
ULTRASONIC RANGE MEASUREMENT UNIT
211
202
210
INPUT/OUTPUT INTERFACE
260
COMMUNICATION INTERFACE
230
WORKING STORAGE
200
CPU
212
140
INERTIAL MEASUREMENT UNIT
201
240
FIXED DATA STORAGE
220
PROGRAM STORAGE

FIG. 2

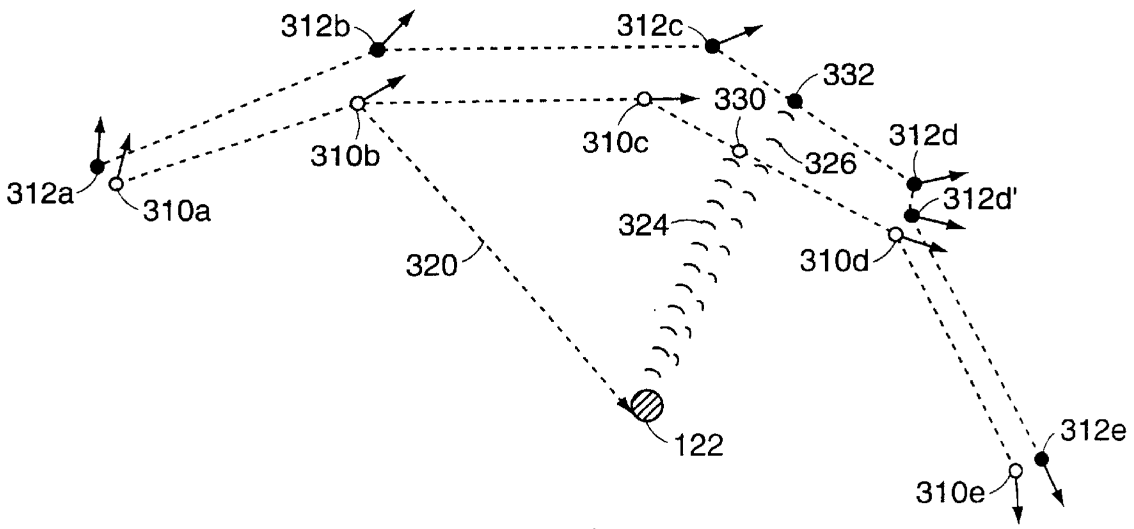

312b
312c
332
330
312d
310c
310b
326
312d'
312a
310a
324
310d
320
122
312e
310e

FIG. 3

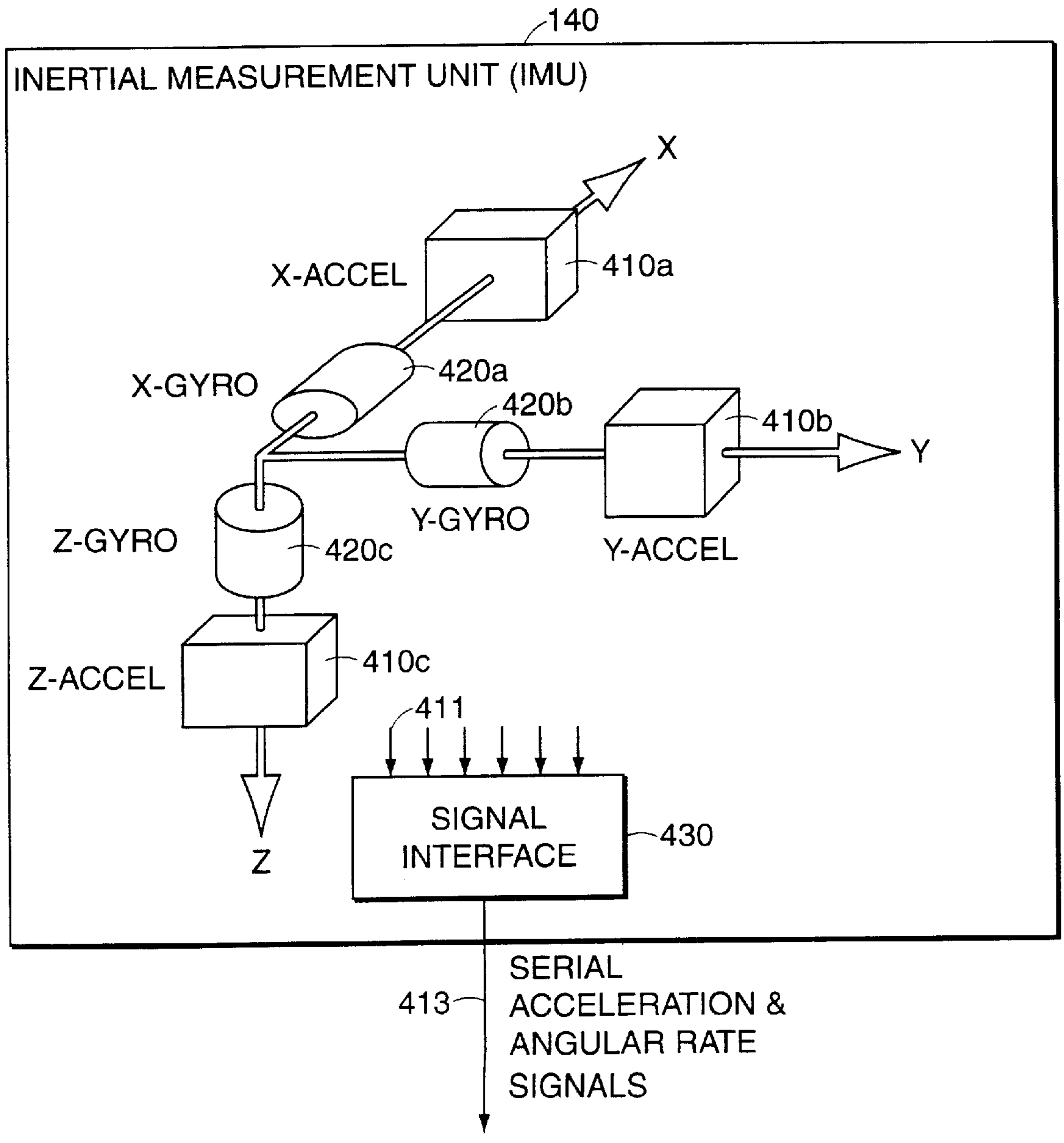

140
INERTIAL MEASUREMENT UNIT (IMU)
X
X-ACCEL
410a
X-GYRO
420a
420b
410b
Y
Y-GYRO
Y-ACCEL
Z-GYRO
420c
Z-ACCEL
410c
411
SIGNAL
INTERFACE
430
Z
413
SERIAL
ACCELERATION &
ANGULAR RATE
SIGNALS

FIG. 4

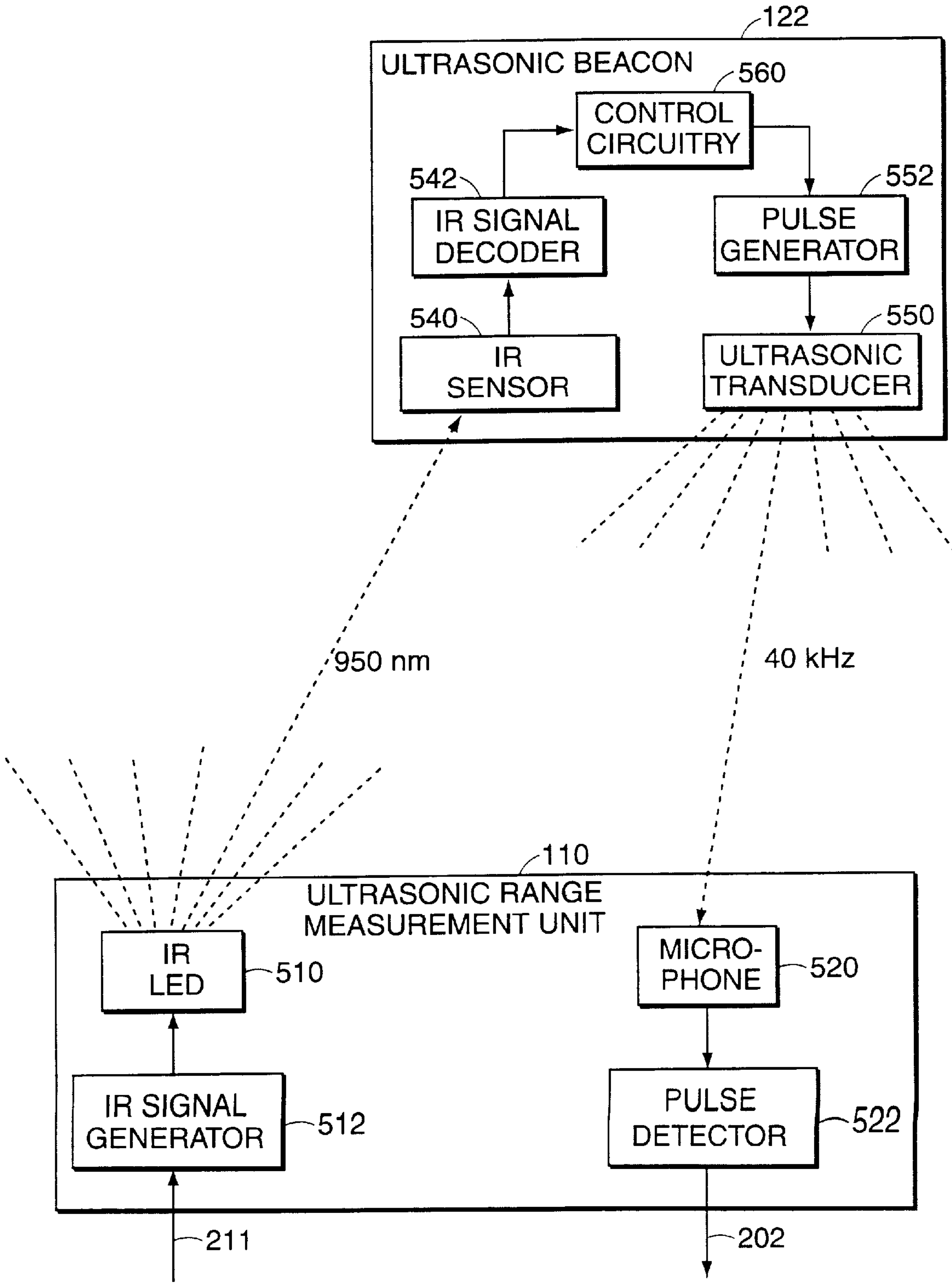

122
ULTRASONIC BEACON
560
CONTROL CIRCUITRY
542
IR SIGNAL DECODER
552
PULSE GENERATOR
540
IR SENSOR
550
ULTRASONIC TRANSDUCER
950 nm
40 kHz
110
ULTRASONIC RANGE MEASUREMENT UNIT
IR LED
510
MICRO-PHONE
520
IR SIGNAL GENERATOR
512
PULSE DETECTOR
522
211
202

FIG. 5

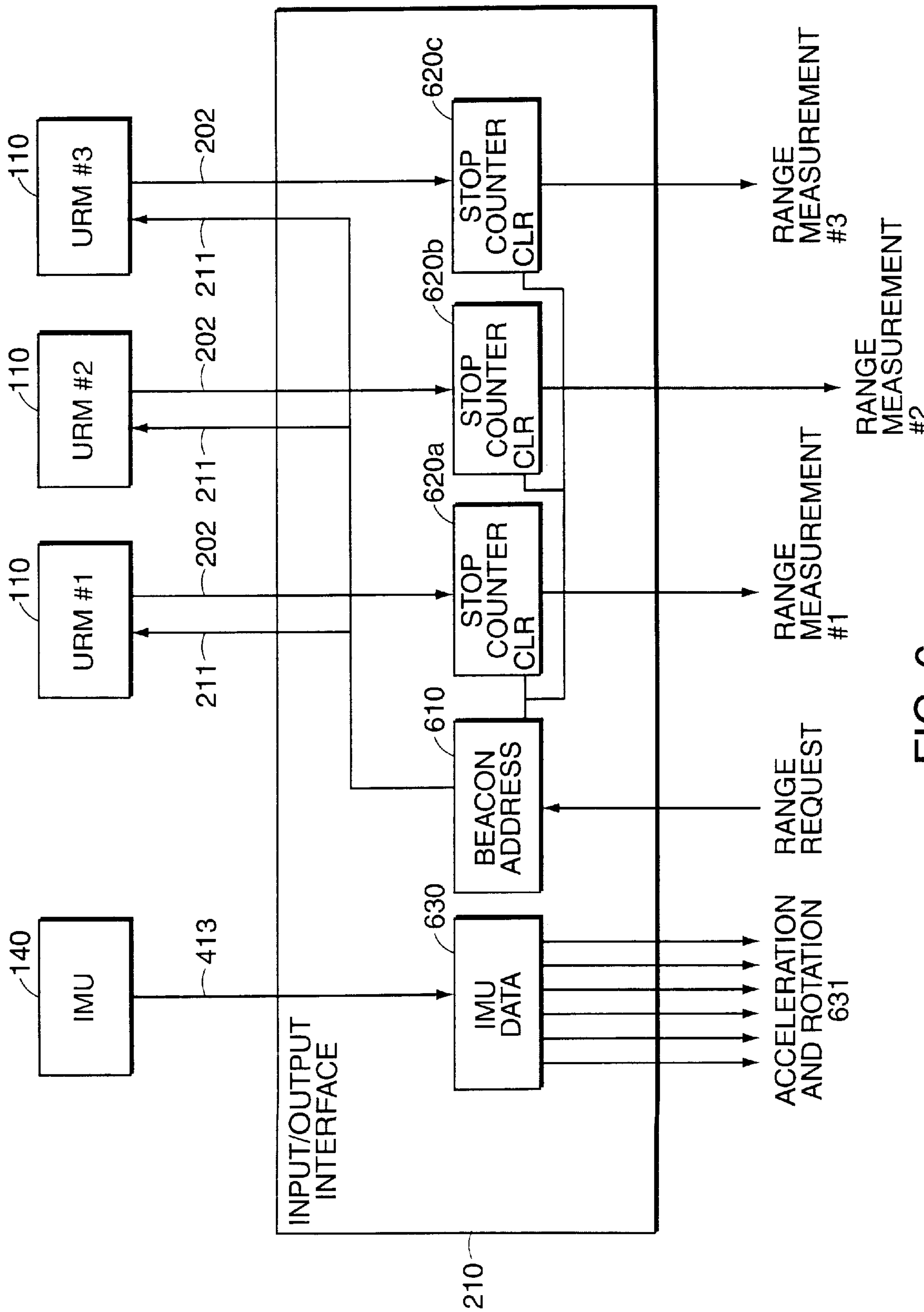

110
URM #3
110
URM #2
110
URM #1
140
IMU
202
211
202
211
202
211
413
620c
STOP
COUNTER
CLR
620b
STOP
COUNTER
CLR
620a
STOP
COUNTER
CLR
610
BEACON
ADDRESS
630
IMU
DATA
INPUT/OUTPUT
INTERFACE
210
RANGE
MEASUREMENT
#3
RANGE
MEASUREMENT
#2
RANGE
MEASUREMENT
#1
RANGE
REQUEST
ACCELERATION
AND ROTATION
631

FIG. 6

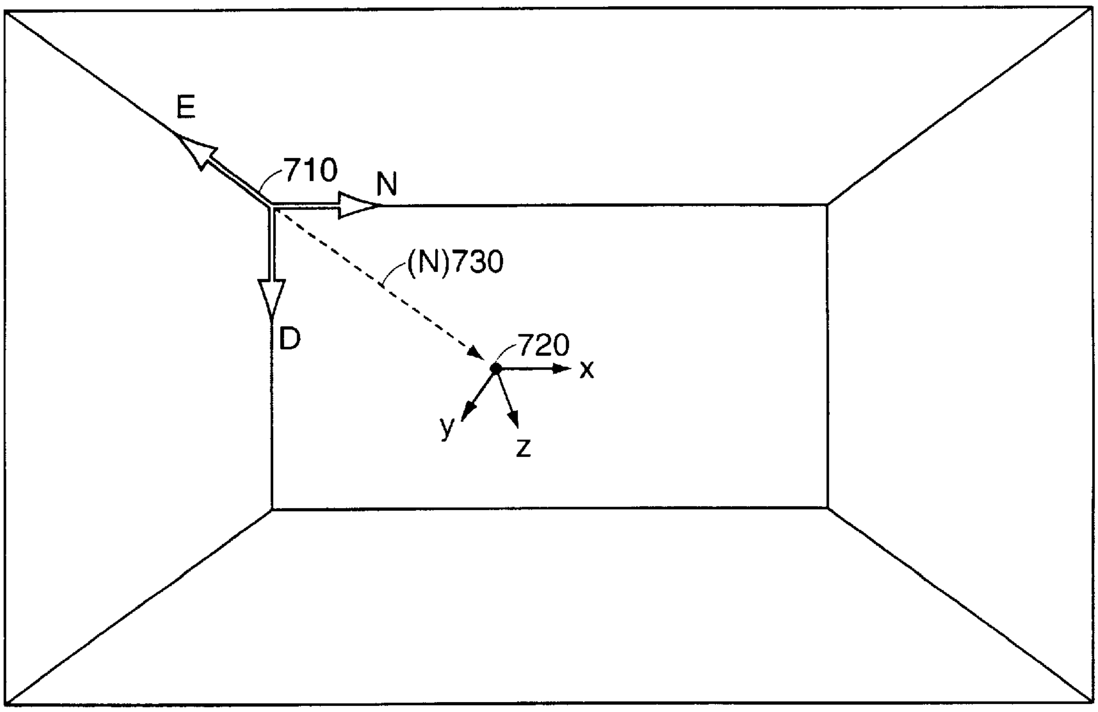

E
710
N
(N)730
D
720
x
y
z

FIG. 7a

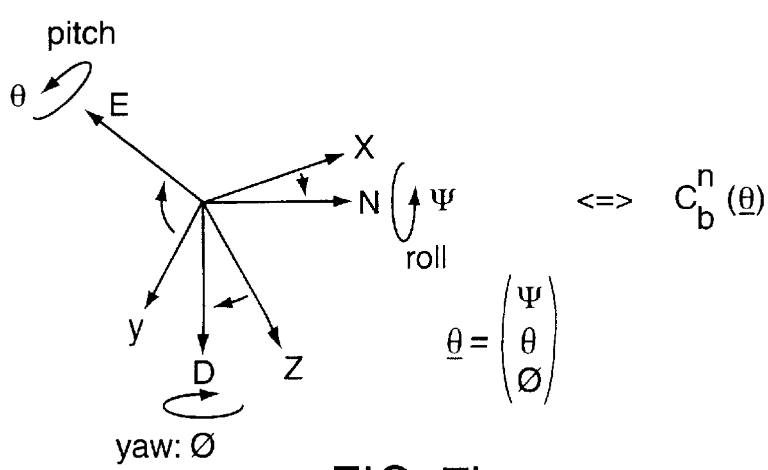

pitch
θ
E
X
N
Ψ
roll
<=>
$C_b^n(\underline{\theta})$
y
D
Z
$\underline{\theta} = \begin{pmatrix} \Psi \\ \theta \\ \varnothing \end{pmatrix}$
yaw: Ø

FIG. 7b

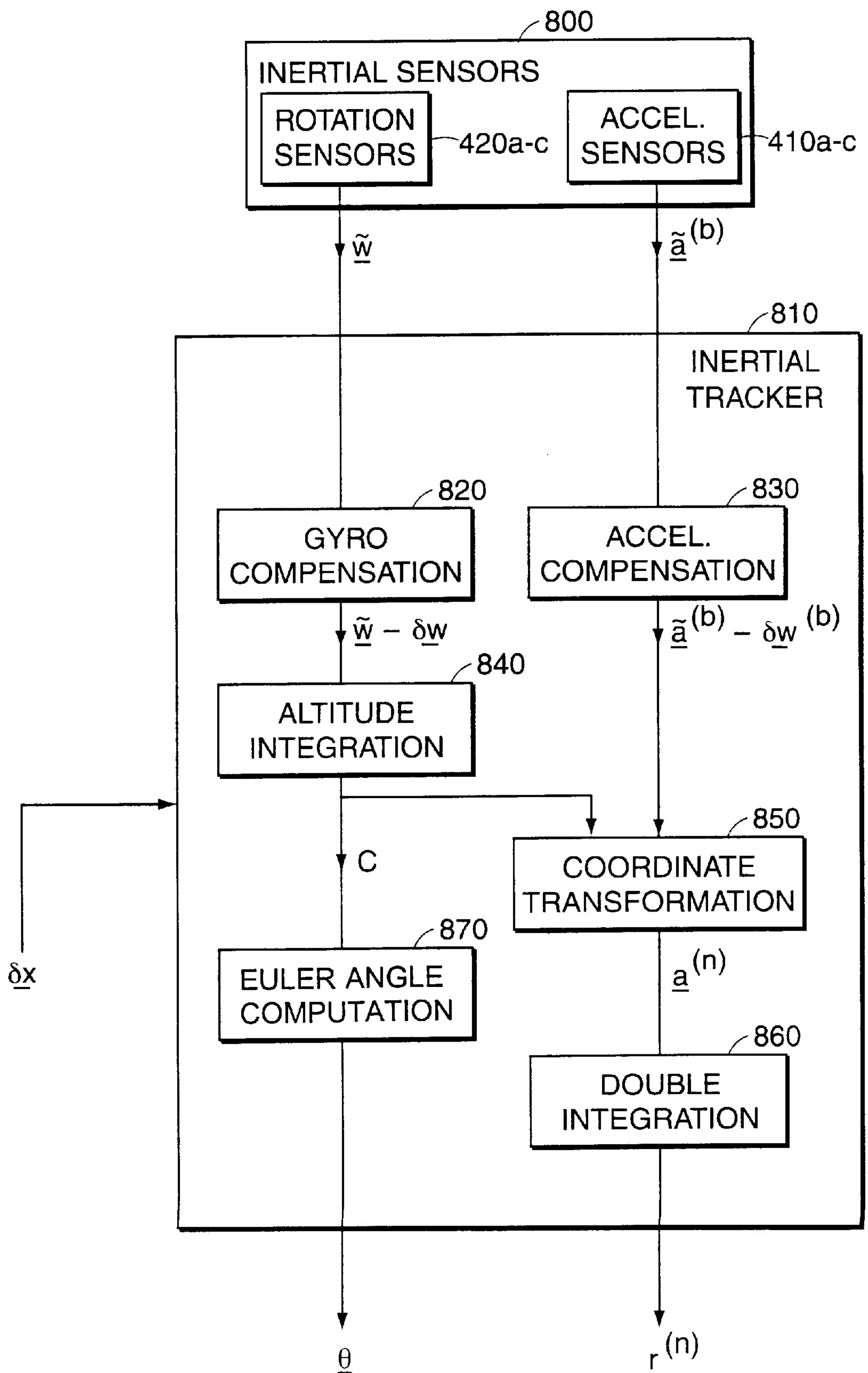

800
INERTIAL SENSORS
ROTATION SENSORS
420a-c
ACCEL. SENSORS
410a-c
$\tilde{\underline{w}}$
$\tilde{\underline{a}}^{(b)}$
810
INERTIAL TRACKER
820
GYRO COMPENSATION
830
ACCEL. COMPENSATION
$\tilde{\underline{w}} - \delta\underline{w}$
$\tilde{\underline{a}}^{(b)} - \delta\underline{w}^{(b)}$
840
ALTITUDE INTEGRATION
850
COORDINATE TRANSFORMATION
C
870
EULER ANGLE COMPUTATION
$\underline{a}^{(n)}$
860
DOUBLE INTEGRATION
$\delta\underline{x}$
$\underline{\theta}$
$\underline{r}^{(n)}$

FIG. 8

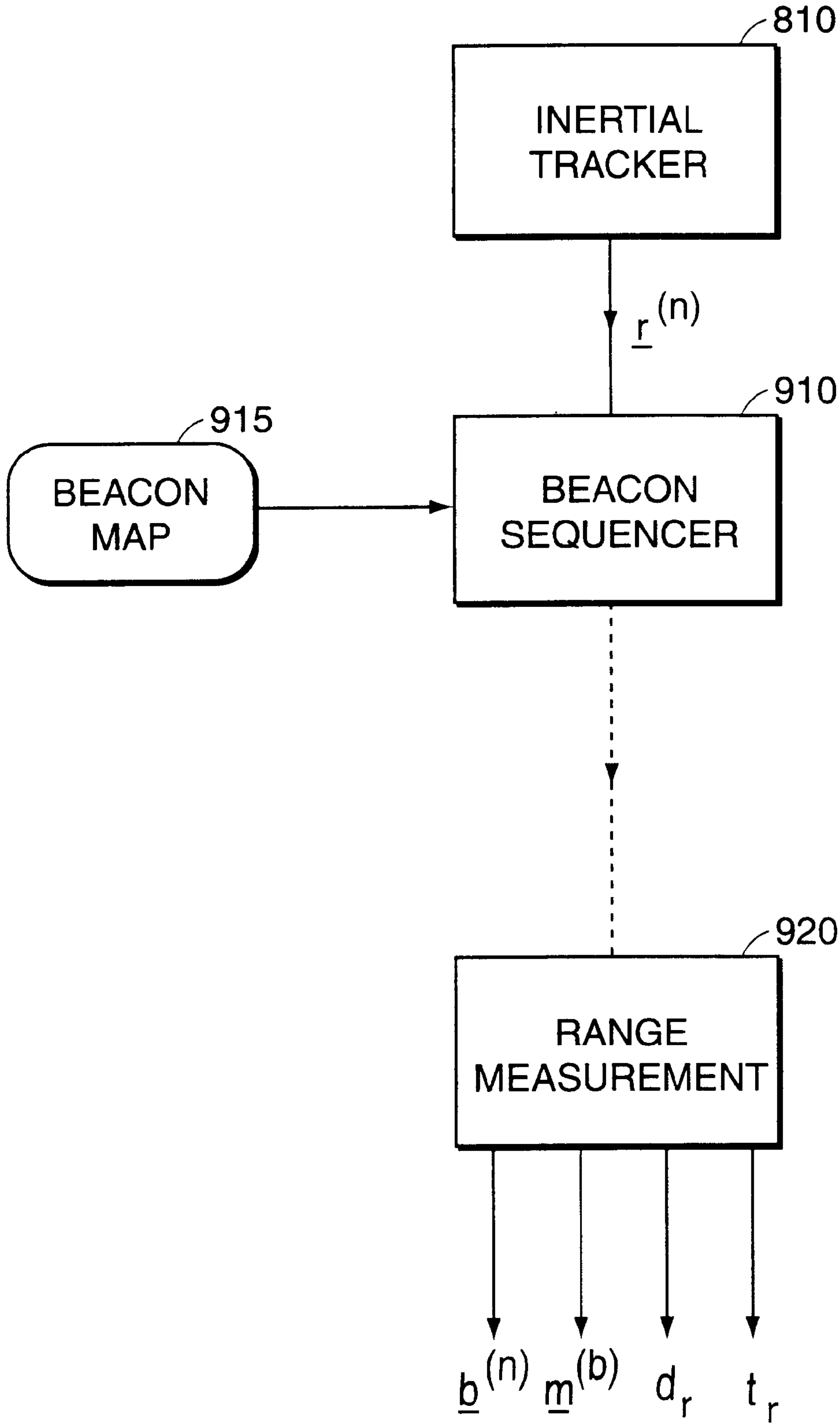

810
INERTIAL TRACKER
r (n)
910
915
BEACON MAP
BEACON SEQUENCER
920
RANGE MEASUREMENT
b (n)
m (b)
d r
t r

FIG. 9

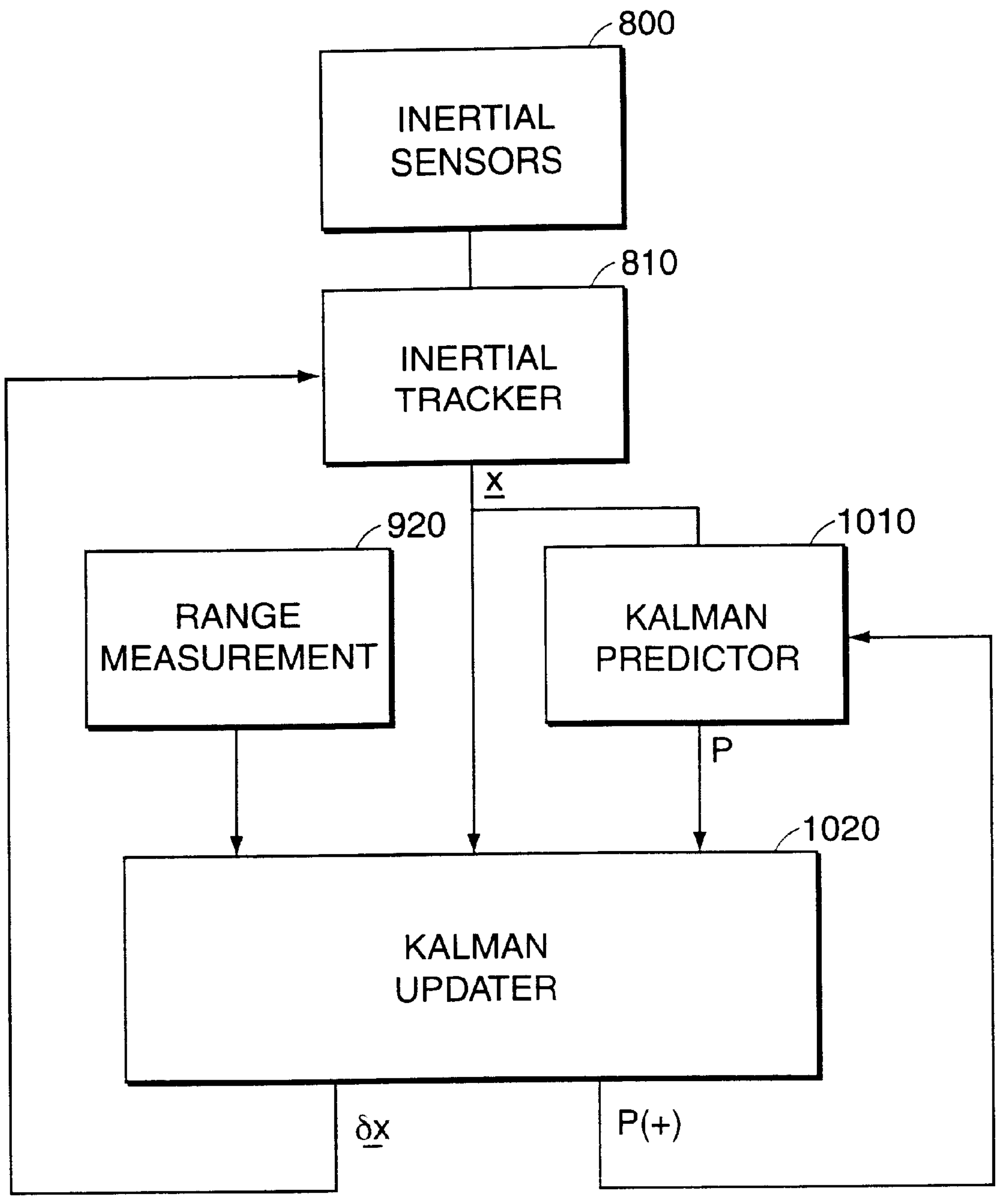

800
INERTIAL SENSORS
810
INERTIAL TRACKER
x
920
RANGE MEASUREMENT
1010
KALMAN PREDICTOR
P
1020
KALMAN UPDATER
δx
P(+)

FIG. 10

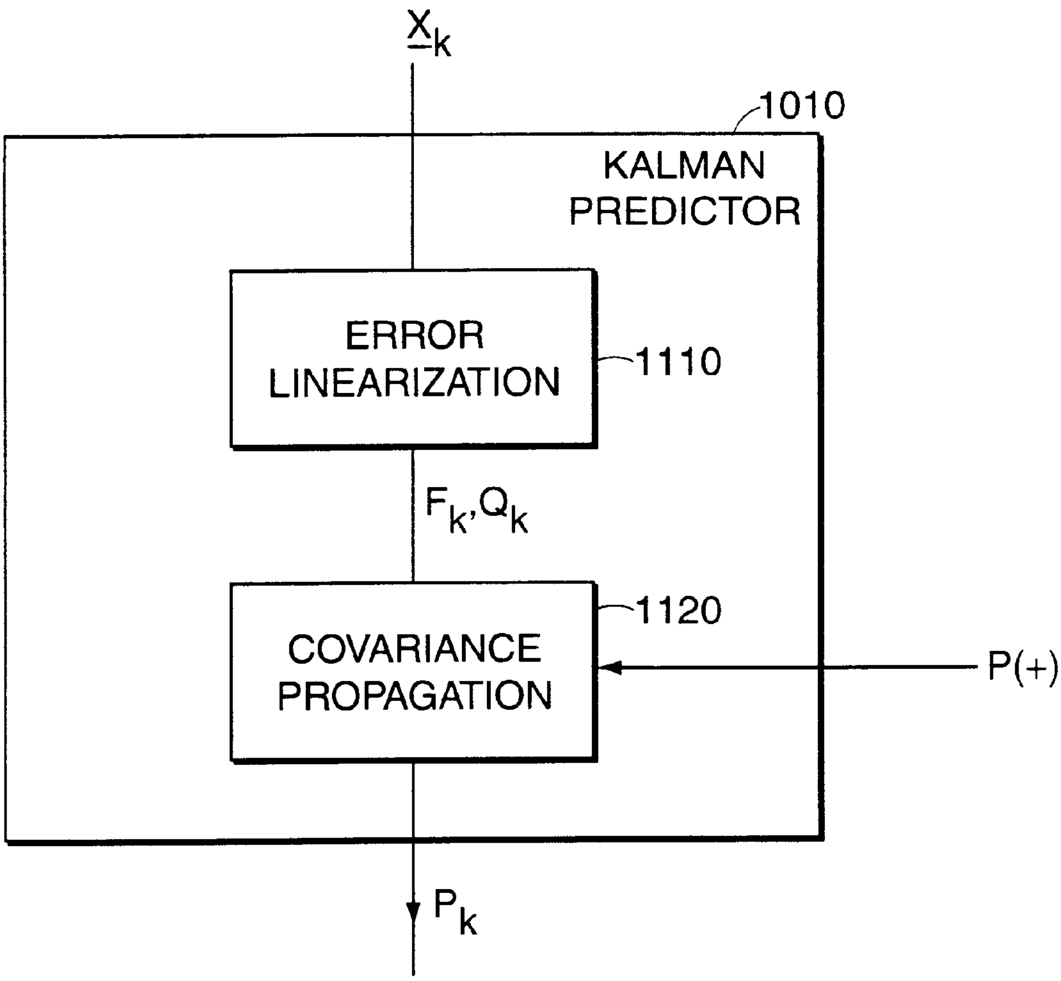

$\underline{X}_k$
1010
KALMAN PREDICTOR
ERROR LINEARIZATION
1110
F_k, Q_k
1120
COVARIANCE PROPAGATION
P(+)
P_k

FIG. 11

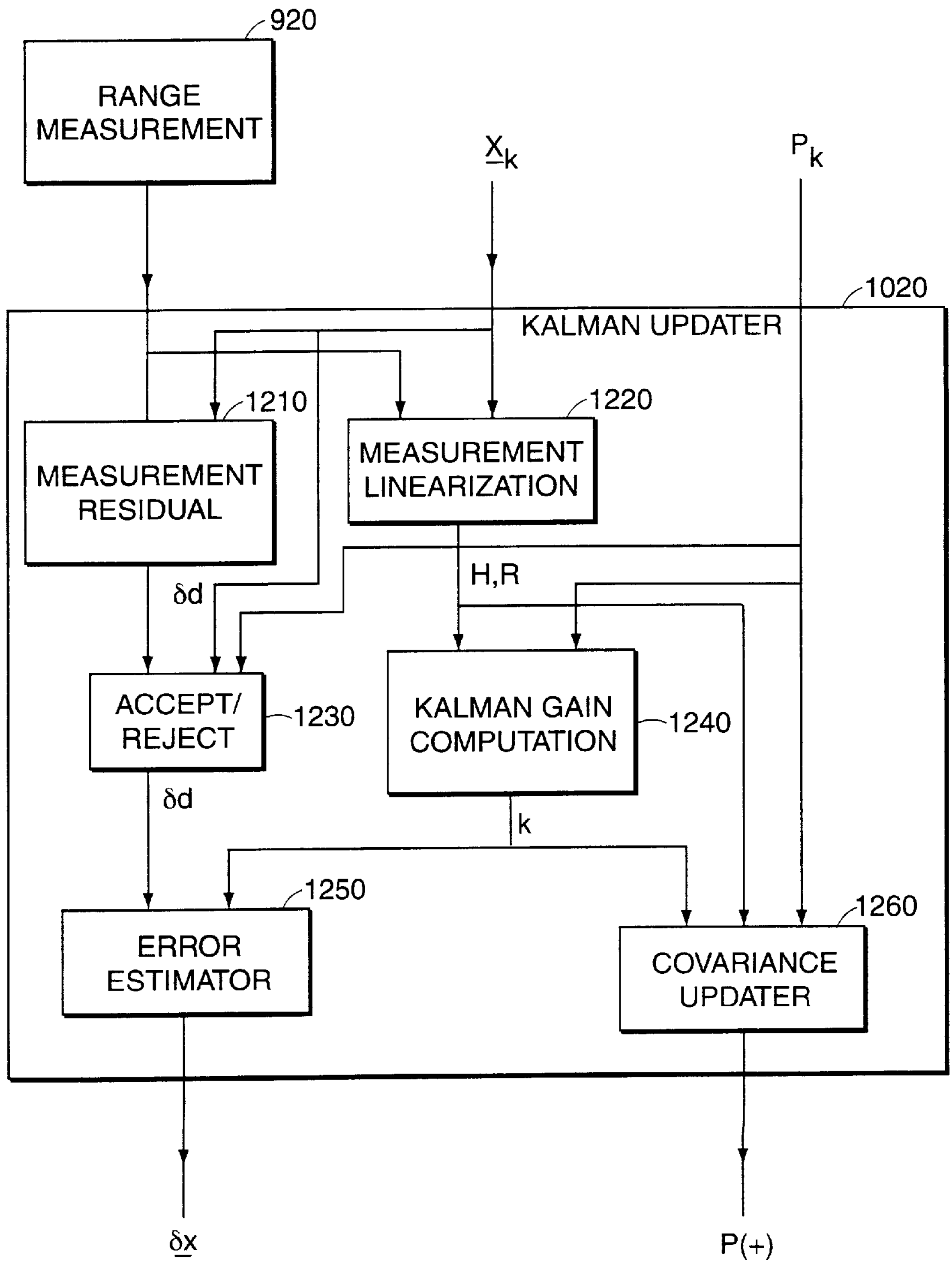

920
RANGE MEASUREMENT
$\underline{X}_k$
P_k
1020
KALMAN UPDATER
1210
MEASUREMENT RESIDUAL
1220
MEASUREMENT LINEARIZATION
H,R
δd
ACCEPT/ REJECT
1230
KALMAN GAIN COMPUTATION
1240
δd
k
1250
ERROR ESTIMATOR
1260
COVARIANCE UPDATER
$\underline{\delta x}$
P(+)

FIG. 12

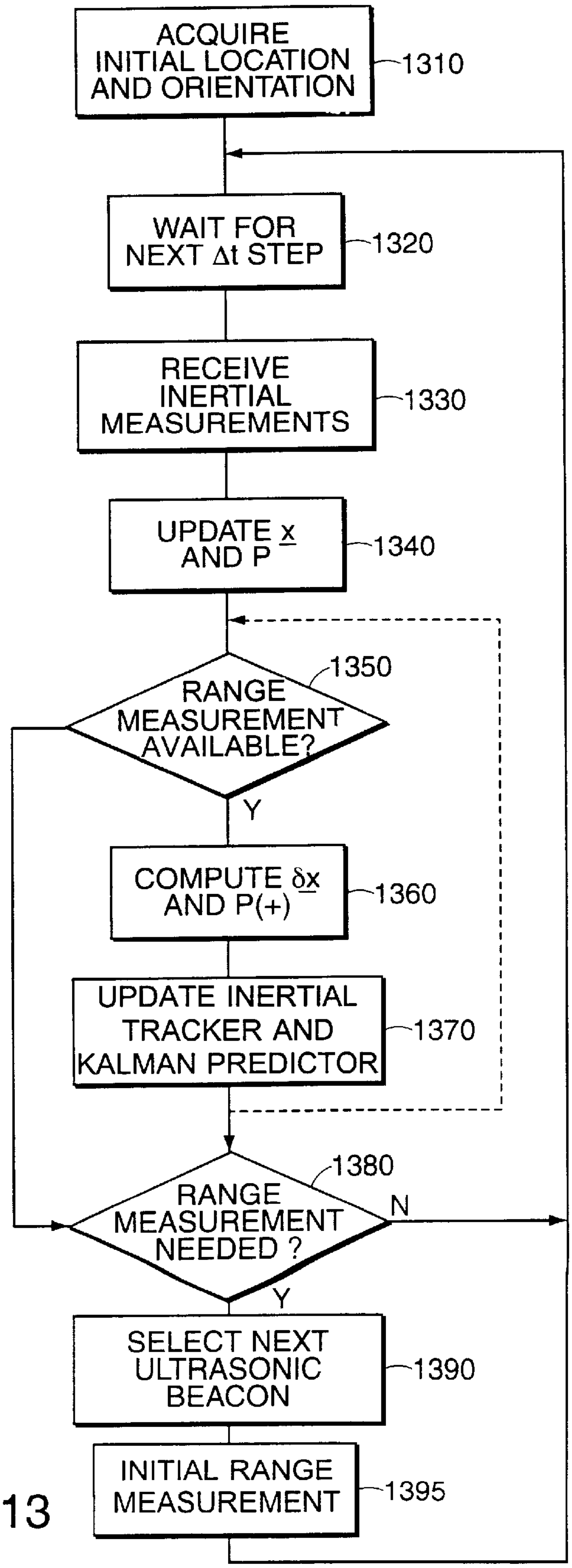

ACQUIRE INITIAL LOCATION AND ORIENTATION
1310
WAIT FOR NEXT Δt STEP
1320
RECEIVE INERTIAL MEASUREMENTS
1330
UPDATE x AND P
1340
RANGE MEASUREMENT AVAILABLE?
1350
Y
COMPUTE δx AND P(+)
1360
UPDATE INERTIAL TRACKER AND KALMAN PREDICTOR
1370
RANGE MEASUREMENT NEEDED ?
1380
N
Y
SELECT NEXT ULTRASONIC BEACON
1390
INITIAL RANGE MEASUREMENT
1395

FIG. 13

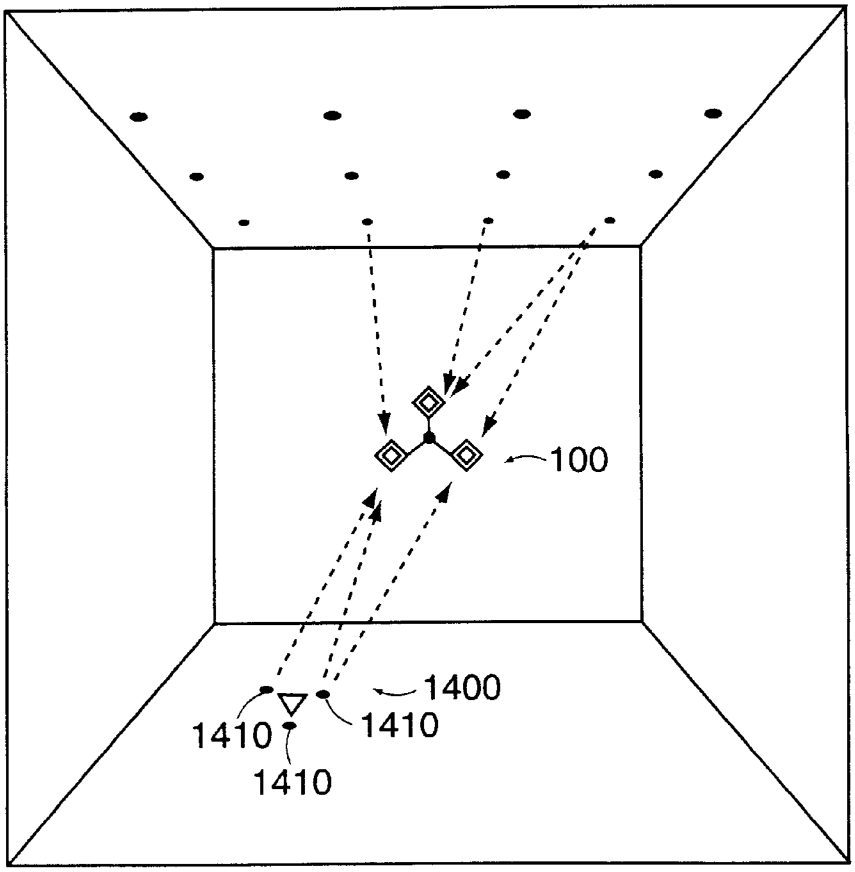


FIG. 14a

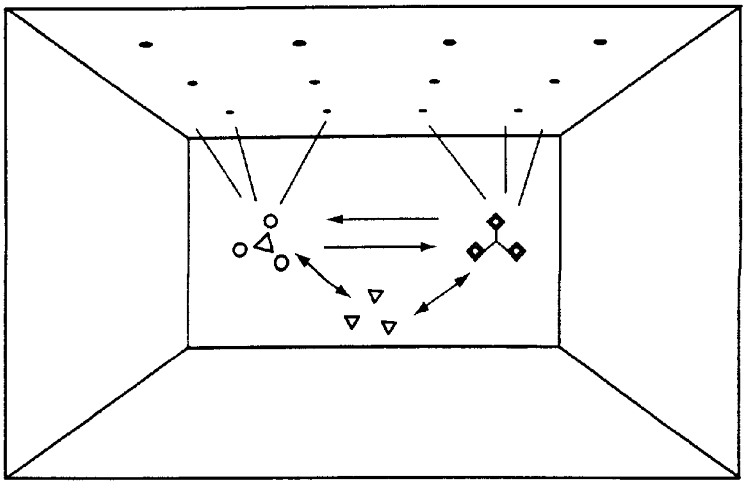


FIG. 14b

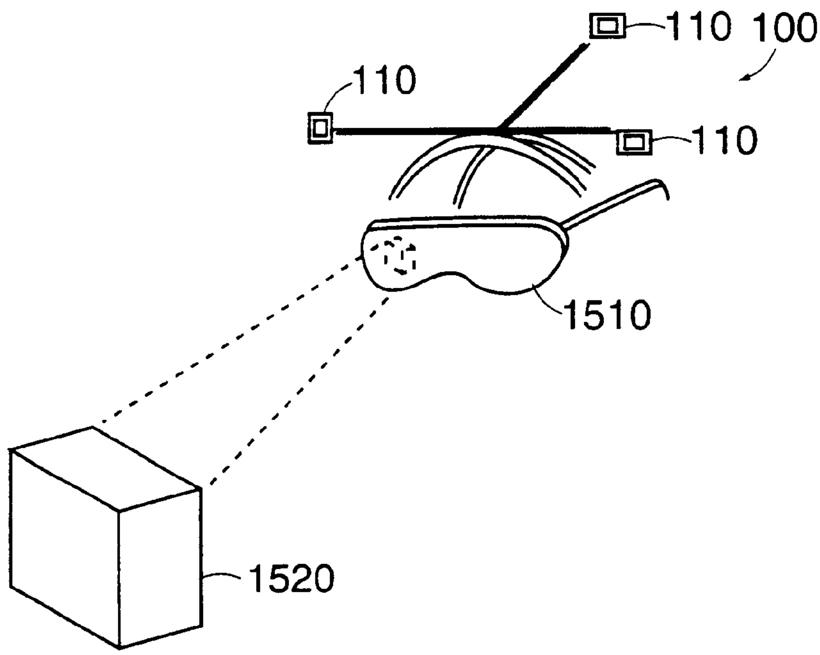


FIG. 15

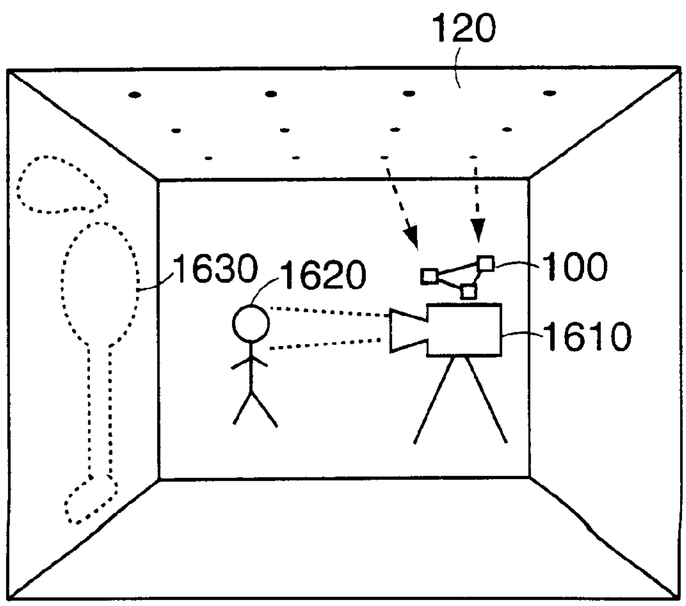


FIG. 16

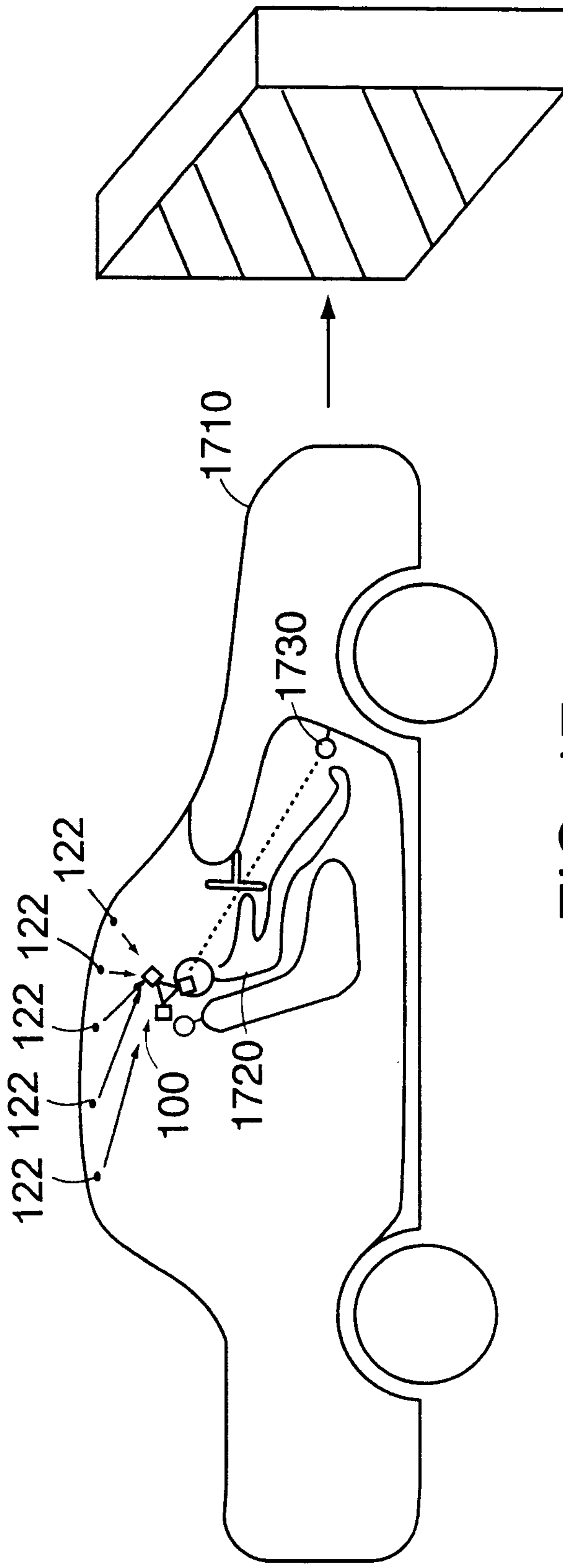


FIG. 17

MOTION TRACKING SYSTEM

BACKGROUND

The invention relates to motion tracking.

Motion tracking can use a variety of measurement modes, including inertial and acoustic measurement modes, to determine the location and orientation of a body.

Inertial motion tracking is-based on measuring linear acceleration and angular velocity about a set of typically orthogonal axes. In one approach, multiple spinning gyroscopes generate forces proportional to the rates at which their spinning axes rotate in response to rotation of a tracked body to which the gyroscopes are attached. These forces are measured and used to estimate angular velocity of the body. Micro-machined vibrating elements and optical waveguide based devices may be used in place of gyroscopes.

Accelerometers generate signals proportional to forces which result from linear acceleration. In an inertial tracking system, the angular velocity and acceleration signals are integrated to determine linear velocity, linear displacement, and total angles of rotation.

As the signals generated by gyroscopic devices are noisy, the integration process results in accumulation of noise components, which is generally known as "drift". Miniaturized and low cost gyroscopic devices typically exhibit greater error. Drift rates can be as high as several degrees per second for a body at rest, and several degrees for every rotation of the body by 90 degrees. Errors in orientation estimates also affect location estimation as the estimated orientation of the body is used to transform acceleration measurements into the fixed reference frame of the environment prior to their integration. Inaccuracy in this transformation can result in gravity appearing as a bias to resulting horizontal acceleration measurements.

One way to correct drift is to use additional sensors, such as inclinometers and a compass to occasionally or continually correct the drift of the integrated inertial measurements. For instance, U.S. Pat. No. 5,645,077, issued to Eric M. Foxlin on Jul. 8, 1997, discloses such an approach. This patent in incorporated herein by reference.

Another approach to motion tracking uses acoustic waves to measure distance between one or more points on a body and fixed reference points in the environment. In one arrangement, termed an "outside-in" arrangement, a set of acoustic emitters at the fixed points on the body emit pulses that are received by a set of microphones at the fixed reference points in the environment. The time of flight from an emitter to a microphone is proportional to an estimate of the distance between the emitter and the microphone (i.e., the range). The range estimates from the emitters to the respective microphones are used to triangulate the location of the emitters. The locations of multiple emitters on the body are combined to estimate the orientation of the body.

Other measurement modes, such as optical tracking of light sources on a body, can also be used to track motion of the body.

SUMMARY

In one aspect, in general, the invention is a method for tracking a motion of a body which includes obtaining two types of measurements associated with the motion of the body, one of the types comprising acoustic measurement, updating an estimate of either an orientation or a position of the body based on one of the two types of measurement, for example based on inertial measurement, and updating the

estimate based on the other of the two types of measurements, for example based on acoustic ranging.

In another aspect, in general, the invention is a method for tracking the motion of a body including selecting one of a set of reference devices, transmitting a control signal to the selected reference device, for example by transmitting a wireless control signal, receiving a range measurement signal from the reference device, accepting a range measurement related to a distance to the selected reference device, and updating a location estimate or an orientation estimate of the body using the accepted range measurement. The method can further include determining a range measurement based on a time of flight of the range measurement signal.

Advantages of the invention include providing a 6-degree-of-freedom tracking capability that can function over an essentially unlimited space in which an expandable constellation of ultrasonic beacons is installed. Inertial measurements provide smooth and responsive sensing of motion while the ultrasonic measurements provide ongoing correction of errors, such as those caused by drift of the inertial tracking component of the system. Small and inexpensive inertial sensors, which often exhibit relatively large drift, can be used while still providing an overall system without unbounded drift. Small, lightweight inertial sensors are well suited for head mounted tracking for virtual or augmented reality display systems. By correcting drift using ultrasonic measurements, drift correction measurements which may be sensitive to external factors such as magnetic field variations, are not needed. The constellation of ultrasonic beacons can be easily expanded as each beacon functions independently and there is no need for wiring among the beacons. The tracking device only relies on use of a small number of ultrasonic beacons at any time, thereby allowing the space in which the tracking device operates to have irregular regions, such as multiple rooms in a building.

Another advantage of the invention is that by using an "inside-out" configuration, there is no latency in acoustic range measurements due to motion of the body after an acoustic wave is emitted.

Yet another advantage of the invention is that tracking continues using inertial measurements even when acoustic measurements cannot be made, for example, due to occlusion of the beacons. Drift in the inertial tracking is then corrected once acoustic measurements can once again be made.

In yet another advantage, the invention provides line-of-sight redundancy whereby one or more paths between emitters and sensors can be blocked while still allowing tracking of a body.

Other features and advantages of the invention will be apparent from the following description, and from the claims.

DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a tracking device and a constellation of acoustic beacons used for tracking the device;

FIG. **2** shows components of a tracking device processor;

FIG. **3** illustrates a combined inertial and acoustic tracking approach;

FIG. **4** shows an inertial measurement unit (IMU);

FIG. **5** shows an ultrasonic range measurement unit (URM) and an ultrasonic beacon;

FIG. **6** shows an input/output interface used in a tracking device processor to interface with inertial and ultrasonic measurement units;

FIG. **7a** illustrates the navigation and body frames of reference;

FIG. **7b** illustrates mutual tracking devices;

FIG. **8** is a signal flow diagram of an inertial tracker;

FIG. **9** is a signal flow diagram of an ultrasonic range measurement subsystem;

FIG. **10** is a signal flow diagram of a tracking device including an inertial tracker and Kalman predictor and updater elements;

FIG. **11** is a signal flow diagram of a Kalman predictor;

FIG. **12** is a signal flow diagram of a Kalman updater;

FIG. **13** is a flowchart of a tracking procedure;

FIG. **14a** illustrates tracking of a second body relative to a first tracked body;

FIG. **14b** illustrates mutual tracking of multiple devices;

FIG. **15** illustrates head mounted display system;

FIG. **16** illustrates a camera tracking system for television; and

FIG. **17** illustrates tracking of bodies in an automobile.

DESCRIPTION

Referring to FIG. **1**, a tracking device **100** which maintains an estimate of its location and orientation is free to move within a large room. For example, tracking device **100** can be fixed to a head-up display (HUD) on an operator's head, and tracking device **100** moves through the room, and changes orientation, as the operator moves and orients his head. Tracking device **100** includes a processor **130** coupled to an inertial measurement unit (IMU) **140** which provides inertial measurements related to linear acceleration and to rates of rotation. Processor **130** uses the inertial measurements to determine motion of tracking device **100** as it moves through the room.

Processor **130** is also coupled to an array of three ultrasonic range measurement units (URM) **110** which are used to receive acoustic signals sent from an ultrasonic beacon array **120**, a "constellation" of beacons. Ultrasonic beacon array **120** includes independent ultrasonic beacons **122** in fixed locations in the environment, for example, arranged on the ceiling of the large room in a regular pattern such as on a grid with 2 foot spacing. Processor **130** uses the signals from particular ultrasonic beacons **122**, as well as known three-dimensional locations of those beacons, to estimate the range to those beacons and thereby sense motion for tracking device **100**. Each ultrasonic beacon **122** sends an ultrasonic pulse **114** in response to infra-red command signal **112** sent from tracking device **100**. In particular, each URM **110** on tracking device **100** broadcasts infra-red (IR) signals to all of the ultrasonic beacons **122**. These IR signals include address information so that only one beacon, or a small number of beacons, recognize each IR signal as intended for it, and responds to the signal. In response to an IR signal, an addressed beacon immediately broadcasts an ultrasonic pulse that is then received by one or more URM **110**. As processor **130** knows that the addressed beacon responded immediately to the IR command, it determines the time of flight by measuring the delay from issuing the IR command to detecting the ultrasonic pulse. The time of flight of the ultrasonic pulse is used to estimate the range to the beacon, which is then used to update the position and orientation of tracking device **100**.

Both the inertial measurements and the ultrasonic signal based measurements have limitations. Relying on either mode of measurement individually is not as accurate as combining the measurements. Tracking device **100** combines measurements from both measurement modes and adjusts its estimate of position and orientation (i.e., 6 degrees of freedom, "6-DOF") to reflect measurements from both modes as they are available, or after some delay. To do this, processor **130** hosts an implementation of an extended Kalman filter (EKF) that is used to combine the measurements and maintain ongoing estimates of location and orientation of tracking device **100**, as well as to maintain an estimate of the uncertainty in those estimates.

Referring to FIG. **2**, processor **130** includes a central processing unit (CPU) **200**, such as an Intel 80486 microprocessor, program storage **220**, such as read-only memory (ROM), and working storage **230**, such as dynamic random-access memory (RAM). CPU **200** is also coupled to an input/output interface **210** which provide an interface to IMU **140** and the URM **110**. Input/output interface **210** includes digital logic that provides digital interfaces to IMU **140** and the URM **110**.

IMU **140** provides a serial data stream **201** encoding inertial measurements. Input/output interface **210** converts this serial data to a parallel form **212** for transfer to CPU **200**. Each URM **110** accepts a serial signal **211** that is used to drive an IR light emitting diode **510** to broadcast the IR control signals to ultrasonic beacons **122** (FIG. **1**). Input/output interface **210** accepts address information from CPU **200** identifying one or more ultrasonic beacons and provides the serial signal to each of the URM **110** which then impose the serial signal on an IR transmission (e.g., by amplitude modulation). The same serial signal is provided to all the URMs **110**, which concurrently broadcast the same IR signal. Each URM **110** provides in return a logical signal **202** to input/output interface **210** indicating arrivals of ultrasonic pulses. Input/output interface **210** includes timers that determine the time of flight of ultrasonic pulses from the beacons, and thereby determines range estimates to the beacons. These range estimates are provided to CPU **200**.

An implementation of a tracking algorithm is stored in program storage **220** and executed by CPU **200** to convert the measurements obtained from input/output interface **210** into position and orientation estimates. CPU **200** is also coupled to fixed data storage **240**, which includes information such as a predetermined map of the locations of the ultrasonic beacons, and the locations of the microphones of the URM **110**. Processor **130** also includes a communication interface **260** for coupling CPU **200** with other devices, such as a display device **280** that modifies its display based on the position and orientation of tracking device **100**.

Operation of the system can be understood by referring to FIG. **3**, a two-dimensional view of the room shown in FIG. **1** (from above). The sequence of open circles and arrows **310a–e** represent the actual location and orientation of tracking device **100** at each of a sequence of time steps. Based on prior measurements, and on inertial measurements at the first time step, filled circle and arrow **312a** represent the estimate by tracking device **100** of the location and orientation of the tracking device at the first time step. At the next time step, tracking device **100** moves to position **310b**, and based on a new inertial measurement, tracking device **100** updates its position estimate to **312b**. This is repeated for the next time step with actual position **310c** and estimated position **312c**.

After reaching position **310b**, tracking device **100** sends an IR command addressed to one of the ultrasonic transducers **122**, illustrated by dotted line **320**. After receiving the IR command (with essentially no delay), ultrasonic trans-

ducer **122** transmits an ultrasonic pulse, illustrated by wave **324**. Wave **324** reaches tracking device **100** some time later, at actual location **330**. Based on the time of arrival, tracking device **100** estimates that it was at position **332** when wave **326** reached it.

At the next time step, tracking device **100** first estimates its position **312***d* based on an inertial measurement. Using range information related to the separation of the location of ultrasonic transducer **122** and location **332** and a measured time of flight of the ultrasonic wave, tracking device **100** computes a refined position estimate **312***d*'. The process repeats using inertial measurements at true position **310***e* and estimated position **312***e*.

In general, both an inertial measurement and an ultrasonic measurement can be used at each time step, although ultrasonic measurement can be made less frequently. At each time step, both location and orientation (attitude) is updated. The ultrasonic pulses can provide information related to both location and orientation through the use of multiple microphones that are displaced relative to one another.

Referring to FIG. **4**, inertial measurement unit (IMU) **140** includes three angular rate sensors (e.g., micro-machined vibrating rotation sensors or small rotating gyroscopes) **420***a–c*, and three linear acceleration sensors **410***a–c*. The sensors are arranged to lie along three orthogonal axes that remain fixed in the frame of reference of tracking device **100**. Each acceleration sensor provides a signal that is generally proportional to the acceleration along the corresponding axis, and each angular rate sensor provides a signal that is generally proportional to the rate of rotation about the corresponding axis.

As the orientation of inertial measurement unit **140** changes, the signals such as the acceleration signals correspond to changing directions in the fixed (navigation) reference frame of the room. Inertial measurement unit **140** also includes a signal interface **430** which accepts the signals **411** from each of the six accelerometers and angular rate sensors, and transmits a serial data stream **413** which multiplexes digital representations of the acceleration and angular rate signals. As is discussed further below, the acceleration and angular rate signals are imperfect, and may exhibit additive bias and scaling inaccuracies. These scaling and bias inaccuracies may depend on the motion of the device.

Referring to FIG. **5**, each ultrasonic measurement unit **110** includes an infra-red (IR) light-emitting diode (LED) **510** that is driven by IR signal generator **512**. Signal generator **512** accepts serial signal **211** from input/output interface **210** (FIG. **2**) and drives IR LED **510** to transmit that signal to one or more ultrasonic beacon **122**. The address of an ultrasonic beacon to which a range is desired is encoded in serial signal **211**. Each ultrasonic beacon **122** includes an IR sensor **540** which, if there is a sufficiently short unobstructed path between ultrasonic range measurement unit **110** and that ultrasonic beacon, receives the IR signal which is then decoded by IR signal decoder **542**. This decoded signal includes the address information transmitted by the ultrasonic range measurement unit. Control circuitry **560** receives the decoded IR signal, and determines whether that ultrasonic beacon is indeed being addressed, and if so, signals a pulse generator **552** to provide a signal to an ultrasonic transducer **550** which generates an ultrasonic pulse. The pulse passes through the air to ultrasonic range measurement unit **110** where a microphone **520** receives the ultrasonic pulse and passes a corresponding electrical signal to a pulse detector **522** which produces a logical signal indicating arrival of the pulse. This pulse detection signal is passed to input/output interface **210** (FIG. **2**). As discussed below, the time of flight is not a perfectly accurate measurement of range. Error sources include timing errors in detection of the pulse, acoustic propagation rate variations, for example due to air temperature or air flow, and non-uniform in different directions propagation of the ultrasonic wave from the ultrasonic beacon.

Input/output interface **210** includes circuitry (i.e., a programmable logic array) which implements logical components shown in FIG. **6**. An IMU data buffer **630** accepts serially encoded acceleration and angular rate data **413** from IMU **140**, and provides the six acceleration and rotation measurements **631** as output to CPU **200**. Input/output interface **210** also includes a beacon address buffer **610**. CPU **200** (FIG. **2**) provides an address of the ultrasonic beacon to which a range should be measured. Beacon address buffer **610** stores the address and provides that address in serial form to each of the URMs **110**. At the same time that the address is transmitted by each of the URM **110** (and received by the ultrasonic beacons **122**), three counters **620***a–c* are reset and begin incrementing from zero at a fixed clocking rate (e.g., 2 MHz). When each URM **110** detects the ultrasonic pulse from the beacon, the corresponding pulse detection signal is passed to the corresponding counter which stops counting. The counts are then available to CPU **200** as the measurements of the time of flight of the ultrasonic pulse from the ultrasonic beacon to each URM **110**.

Referring to FIGS. **7***a–b*, tracking device **100** (FIG. **1**) determines its location in the navigation reference frame of the room, shown as axes **710**, labeled N (north), E (east), and D (down). Location $\underline{r}^{(n)}$ **730** is a vector with components $(r_N^{(n)}, r_E^{(n)}, r_D^{(n)})^T$ of the displacement from axes **710** in the N, E, and D directions respectively. Tracking device **100** also determines its attitude (orientation).

Referring to FIG. **7***b*, attitude is represented in terms of the roll, pitch, and yaw (Euler) angles, $\underline{\theta}=(\psi, \theta, \phi)^T$, needed to align the body attitude, represented by coordinate axes **720**, with the navigation attitude represented by coordinate axes **710**. The three Euler angles are represented as a 3×3 direction cosine matrix, $C_b^n(\underline{\theta})$, which transforms a vector of coordinates in the body frame of reference by essentially applying in sequence yaw, pitch, and then roll motions around the z, y, and then x axes. The direction cosine matrix can be defined as

$$C(\underline{\theta}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The superscript and subscript notation C_b^n signifies that the matrix takes a vector in the "b" (body) reference frame and provides a vector in the "n" (navigation) reference frame.

Referring to FIG. **8**, inertial sensors **800**, including rotation sensors **420***a–c* and acceleration sensors **410***a–c*, provide inertial measurement signals to an inertial tracker **810**. Inertial tracker **810** implements a discrete time approximation of the signal flow shown in the FIG. **8**. Inertial tracker **810** includes several stages. First, gyroscope compensation **820** modifies the (vector) angular rate signal $\tilde{\underline{\omega}}$ to account for bias in the measurement. In this example, only an additive bias $\delta\underline{\omega}$ is corrected. Other biases such as a multiplicative error (e.g., an incorrect scale factor), and errors due to mounting inaccuracies can be corrected as well. Accelerometer compensation **830** similarly corrects for an additive bias $\delta\underline{a}^{(b)}$ on the acceleration signals $\underline{a}^{(b)}$. As is

discussed fully below, several parameters, including the bias terms $\underline{\delta\omega}$ and $\underline{\delta a}^{(b)}$, are estimated using ultrasonic measurements.

Attitude integration **840** updates the attitude estimate based on the bias corrected rotation signal. In this example, attitude integration is performed using a direction cosine representation of the attitude. A discrete time implementation of the continuous differential equation $\dot{C}_b^n(t)=C_d^n(t)\, S(\underline{\omega}(t))$ is used to update the direction cosine matrix at a fixed rate, typically between 100 and 200 per second. Changing notation to a discrete time system (e.g., $C_k=C_b^n(k\Delta t)$), the discrete time update of the direction cosine matrix is implemented as

$$C_k = C_{k-1}\left(I + \frac{\sin\delta\theta}{\delta\theta}S(\underline{\delta\theta}) + \frac{1-\cos\delta\theta}{\delta\theta^2}S(\underline{\delta\theta})^2\right)$$

where

$$\underline{\delta\theta} = \frac{\underline{\omega}_{k-1}+\underline{\omega}_k}{2}\Delta t,\ \delta\theta = \|\underline{\delta\theta}\|$$

and

$$S(\underline{\delta\theta}) = \begin{bmatrix} 0 & -\delta\theta_z & \delta\theta_y \\ \delta\theta_z & 0 & -\delta\theta_x \\ -\delta\theta_y & \delta\theta_x & 0 \end{bmatrix}$$

is the skew symmetric matrix of $\underline{\delta\theta}$. Note that $S(\underline{\delta\Theta})$ satisfies

$$S(\underline{\delta\theta})^2=\delta\theta^2 I-\underline{\delta\theta}\ \underline{\delta\theta}^T.$$

In order to ensure that C_k truly is a direction cosine matrix, its rows are orthonormalized after each iteration to remove any numerical or approximation errors that may have entered into its entries.

Based on the tracked direction cosine matrix C_k, coordinate transformation **850** accepts the bias corrected acceleration signal in the body reference frame and outputs an acceleration signal in the navigation reference frame according to

$$\underline{a}_k^{(n)}=C_k(\underline{\tilde{a}}_k^{(b)}-\underline{\delta a}_k^{(b)})+(0,0,-g)^T.$$

Double integration **860** then computes the velocity and position according to

$$\underline{v}_k^{(n)} = \underline{v}_{k-1}^{(n)} + \frac{\underline{a}_{k-1}^{(n)}+\underline{a}_k^{(n)}}{2}\Delta t, \quad \text{and}$$

$$\underline{r}_k^{(n)} = \underline{r}_{k-1}^{(n)} + \underline{v}_{k-1}^{(n)}\Delta t + \frac{2\underline{a}_{k-1}^{(n)}+\underline{a}_k^{(n)}}{6}\Delta t^2.$$

Euler angle computation **870** takes the direction cosine matrix and outputs the corresponding Euler angles. The output of inertial tracker **810** is $(\underline{\theta}, \underline{r}^{(n)})^T$. The state of the inertial tracker includes a 15-dimensional vector composed on five sets of three-dimensional values

$$\underline{x}=(\underline{74}, \underline{\omega}, \underline{r}^{(n)}, \underline{v}^{(n)}, \underline{a}^{(n)})^T.$$

As is discussed fully below, inertial tracker **810** receives error update signals $\underline{\delta x}$ derived from ultrasonic range measurements that it uses to correct the attitude, velocity, and position values, and to update the parameters of the gyroscope and accelerometer bias correction elements.

Referring to FIG. **9**, a beacon sequencer **910** receives location estimates $\underline{r}^{(n)}$ from inertial tracker **810**. Using a beacon map **915** of the locations (and addresses) of the ultrasonic beacons **122** (shown in FIG. **1**), beacon sequencer **910** determines which beacon to trigger at each time step in order to generate ultrasonic range measurements. For instance, beacon sequencer **910** determines the closest beacons to the current location, and cycles among these beacons on each time step. As the location estimate changes, the set of closest beacons also, in general, changes. After beacon sequencer **910** triggers each of the beacons in turn, the corresponding ultrasonic pulses arrive and are detected by the tracking device. Each pulse generates one range measurement for each microphone used to detect the pulse. In this embodiment, each pulse generates a set of three range measurements, one from each of the microphones in the three URM **110**.

Referring still to FIG. **9**, range measurement **920** corresponds to the process of receiving an ultrasonic range estimate. The relevant parameters for a range measurement are the location of the addressed beacon, $\underline{b}^{(n)}$, the location of the microphone used to detect the pulse, $\underline{m}^{(b)}$, the range estimate itself, d_r, and the time the pulse was detected, t_r, which is used to correct for latency in the measurements. Note that if the location estimate had no error, and the range estimate was perfectly accurate, then the range estimate would satisfy

$$d_r=\|\underline{b}^{(n)}-(\underline{r}^{(n)}(t_r)+C_b^n(t_r)\underline{m}^{(b)})\|.$$

Deviations from this equality are used to correct the parameters and outputs of inertial tracker **810**.

A complementary Kalman filter is used by tracking device **100** to improve the tracked location and orientation estimate by incrementally updating the tracked quantities as the range measurements come in. Referring to FIG. **10**, the approach involves two related components. As inertial tracker **810** updates its output $\underline{x}$, a Kalman predictor **1010** maintains an estimated covariance matrix P of the error in $\underline{x}$. For instance, in the absence of any drift compensation in inertial tracker **810**, the covariance matrix P would correspond to an ever increasing error.

The second component used in this approach is a Kalman updater **1020** which accepts information from range measurement **920** and using this measurement information determines an estimate of the accumulated error $\underline{\delta x}$ which it feeds back to inertial tracker **810** where it is used to update $\underline{x}$. Also, after each ultrasonic measurement, Kalman updater **1020** computes a new estimated covariance matrix P(+) of the error in $\underline{x}$ after the update, which it feeds back to Kalman predictor **1010**. Each ultrasonic measurement partially corrects the output of inertial tracker **810**. A continuous series of ultrasonic updates ensures that the error remains small.

Inertial tracker **810** is a nonlinear processor of its inputs, and therefore, a formulation of a Kalman filter for a purely linear filter driven by Gaussian noise is not appropriate. Using what is generally known as an “extended Kalman filter” (EKF), a linearized dynamical system model which characterizes the propagation of error in the output $\underline{x}$ of inertial tracker **810** is used. The error that the EKF models is

$$\underline{\delta x}=(\underline{\phi}, \underline{\delta\omega}^{(b)}, \underline{\delta r}^{(n)}, \underline{\delta v}^{(n)}, \underline{\delta a}^{(b)})^T$$

with the components corresponding to the components of the vector output of the inertial tracker. Note that the error term $\underline{\delta a}^{(b)}$ is modeled in the body coordinate system rather than in the navigation coordinate system, and that the other elements correspond directly to errors in the output of inertial tracker **810**. The parameters of the linearized error propagation model include a state transition matrix, and a

covariance matrix of a driving noise which is assumed to drive this error model. Both the state transition matrix and the driving noise covariance depend on the output of inertial tracker. In the absence of any measurements, the mean of the error process remains zero. However, the covariance of the error grows. The linearized model of error propagation is

$$\underline{\delta x}_k=F(\underline{x}_{k-1})\underline{\delta x}_{k-1}+\underline{w}_{k-1}.$$

The entries of $F_k=F(\underline{x}_{k-1})$ are derived from a perturbation analysis of the update equations used in inertial tracker **810**, and correspond to the following error propagation equations:

$$\underline{\phi}_k=\underline{\phi}_{k-1}C_b^n\underline{\delta\omega}_{k-1},$$

$$\underline{\delta\omega}_k=\underline{\delta\omega}_{k-1},$$

$$\underline{\delta r}_k=\underline{\delta r}_{k-1}+\Delta t\ \underline{\delta v}_{k-1}-\tfrac{1}{2}\Delta t^2(C_b^n\underline{\delta a}_{k-1}{}^{(b)}-S(\underline{\phi}_{k-1})(\underline{a}_{k-1}{}^{(n)}+(0,0,-g)^T))$$

$$\underline{\delta v}_k=\underline{\delta v}_{k-1}+\Delta t\ \underline{\delta a}_{k-1}{}^{(b)}-\Delta t\ S(\underline{\phi}_{k-1})(\underline{a}_{k-1}{}^{(n)}+(0,0,-g)^T),$$

and

$$\underline{\delta a}_k{}^{(b)}=\underline{\delta a}_{k-1}{}^{(b)}.$$

The covariance Q_k of the process noise w_k is assumed to be diagonal. The entries of this covariance matrix are derived from known sources of error in the inertial measurements provided to inertial tracker **810**, including additive bias errors, scaling errors, alignment errors of the sensors with the body axes, and signal noise from the sensors themselves. The individual variances depend on the output of the inertial tracker as follows:

$$Q_k=\mathrm{diag}\ (\sigma_{\phi_x}{}^2,\sigma_{\phi_y}{}^2,\sigma_{\phi_z}{}^2,\sigma_\omega{}^2,\sigma_\omega{}^2,\sigma_\omega{}^2,\sigma_{r_x}{}^2,\sigma_{r_y}{}^2,\sigma_{r_x}{}^2,\sigma_{v_x}{}^2,\sigma_{v_y}{}^2,\sigma_{v_z}{}^2,\sigma_a{}^2,\sigma_a{}^2,\sigma_a{}^2)$$

where the individual variance terms are parameterized as follows:

$$\sigma_{\phi_x}=\mathrm{GyroScale}\ \omega_x\ \Delta t+\mathrm{GyroAlign}\ (\omega_y+\omega_z)\ \Delta t+\mathrm{GyroNoise}\ \sqrt{\Delta t}$$

$$\sigma_{\phi_y}=\mathrm{GyroScale}\ \omega_y\ \Delta t+\mathrm{GyroAlign}\ (\omega_x+\omega_z)\ \Delta t+\mathrm{GyroNoise}\ \sqrt{\Delta t}$$

$$\sigma_{\phi_z}=\mathrm{GyroScale}\ \omega_z\ \Delta t+\mathrm{GyroAlign}\ (\omega_x+\omega_y)\ \Delta t+\mathrm{GyroNoise}\ \sqrt{\Delta t}$$

$$\sigma_\omega=\mathrm{GyroBiasChangeRate}\ \Delta t$$

$$\sigma_{r_x}=\sigma_{r_y}=\sigma_{r_z}=0$$

$$\sigma_{v_x}=\mathrm{AccelScale}\ a_x\ \Delta t+\mathrm{AccelAlign}\ (a_y+a_z)\ \Delta t+\mathrm{AccelNoise}\ \sqrt{\Delta t}$$

$$\sigma_{v_y}=\mathrm{AccelScale}\ a_y\ \Delta t+\mathrm{AccelAlign}\ (a_x+a_z)\ \Delta t+\mathrm{AccelNoise}\ \sqrt{\Delta t}$$

$$\sigma_{v_z}=\mathrm{AccelScale}\ a_z\ \Delta t+\mathrm{AccelAlign}\ (a_x+a_y)\ \Delta t+\mathrm{AccelNoise}\ \sqrt{\Delta t}$$

$$\sigma_a{}^2=\mathrm{AccelBiasChangeRate}\ \Delta t$$

where GyroScale, AccelScale, GyroAlign, and AccelAlign correspond to degree of uncertainty in calibration coefficients used for instrument error compensation. In general, a non-diagonal process noise covariance can be used.

Referring to FIG. **11**, Kalman predictor **1010** has two stages. An error linearization stage **1110** first computes F_k and Q_k as outlined above. Then, a covariance propagation stage **1120** iteratively updates the error covariance by applying a Kalman filter covariance propagation equation

$$P_k=F_{k-1}P_{k-1}F_{k-1}{}^T+Q_k$$

on each time step. When Kalman predictor **1010** receives an updated covariance P(+), which is produced as a result of an ultrasonic range measurement, that updated covariance replaces the current error covariance P.

Referring to FIG. **12**, Kalman updater **1020** accepts the output of range measurement **920**, as well as the estimate of location and orientation from inertial tracker **810**, and the covariance of the error of the estimate of location and orientation from Kalman predictor **1010**, and computes an error estimate, and an updated covariance that results from applying the error estimate. A first stage of Kalman updater **1020** is measurement residual computation **1210**. The difference between the expected range and the measured range is computed as

$$\delta d_r=d_r-\|\underline{b}^{(n)}-(\underline{r}^{(n)}(t_r)+C_b{}^n(t_r)\underline{m}^{(b)})\|.$$

Note that in general a range measurement is used some time after it was initially detected. In order to account for this latency, estimates of the location and orientation of the tracking device at the time that the acoustic pulse arrived are used rather than the location and orientation at the time that the measurement is used. The current location, orientation, and linear and angular rate estimates are used to extrapolate back to the measurement time to determine $\underline{r}^{(n)}(t_r)$ and $C_b{}^n(t_r)$.

In order to apply the Kalman update equations, this residual is modeled using a linearized observation equation as

$$\delta d_r=H(\underline{x},\underline{b},d_r,\underline{m})\underline{\delta x}+v.$$

The observation matrix $H_k=H(\underline{x}_k,\underline{b},d_r,\underline{m})$ is the linear effect of errors in location and orientation on the error in range measurement. The additive noise v has a variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$. H_k has the form

$$H_k=\Bigg(\frac{b_Dm_E-b_Em_D+r_Em_N-r_Dm_E}{d_r},\ \frac{b_Nm_D-b_Dm_N+r_Dm_N-r_Nm_D}{d_r},\ \frac{b_Em_N-b_Nm_E+r_Nm_E-r_Em_N}{d_r},0,0,0,\ \frac{r_N+m_N-b_N}{d_r},\frac{r_E+m_E-b_E}{d_r},\frac{r_D+m_D-b_D}{d_r},\ 0,0,0,0,0,0\Bigg)$$

The variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$ is derived to model various phenomena associated with ultrasonic range measurement. For example, as the range increases, pulse detection is more difficult, due in part to pulse spreading, and an increased variance is used to model the associated range measurement error. The variance $R(\underline{x}_k,\underline{b},d_r,\underline{m})$ has the form

$$R=\sigma_u{}^2+\sigma_l{}^2$$

and is parameterized as

$$\sigma_u{}^2=\mathrm{NoiseFloor}+\mathrm{NoiseScale}\ d_r$$

and

$$\sigma_l{}^2=(k\Delta t-t_r)H_k(\omega_x,\omega_y,\omega_z,0,0,0,v_x,v_y,v_z,0,0,0,0,0,0))^T$$

The first two terms of H_k can alternatively be set to zero to allow accelerometric tilt correction (if it is more accurate). It the third term is set to zero, yaw drift correction will occur over a longer time period but to higher accuracy.

Kalman updater **1020** includes a measurement accept/reject stage **1230**. Accept/reject stage **1230** takes the measurement residual, $\underline{\delta x}$, and the computed variance, R, of the measurement residual. If the measurement residual is greater in magnitude than a predetermined multiple of the computed standard deviation of the measurement residual, then the measurement is rejected as being suspect, for example, due to premature or late triggering of an ultrasonic pulse detector. Otherwise the measurement residual is further processed to compute the state error estimate, $\underline{\delta x}$. Using Kalman filter update equations, Kalman gain computation **1240** computes the Kalman gain as

$$K=P_kH_k^T(H_kP_kH_k^T+R)^{-1}.$$

Error estimator **1250** then computes the error estimate as $\underline{\delta x}$=K δd, and covariance updater **1260** computes the updated error covariance as

$$P(+)=(I-K\ H)P_k.$$

The components of $\underline{\delta x}$ are then used to update inertial tracker **810**. The computed terms $\underline{\delta\omega}$ and $\underline{\delta a}^{(b)}$ are passed to gyroscope bias correction **820** and accelerometer bias correction **830** (FIG. **8**), respectively, where they are added to the current stored bias parameters. The computed terms $\underline{\delta v}^{(n)}$ and $\underline{\delta r}^{(n)}$ are passed to double integration **860** (FIG. **8**) where they are added to the current estimates of $\underline{v}^{(n)}$ and $\underline{r}^{(n)}$, respectively. Finally, the direction cosine matrix is updated according to

$$C_k\leftarrow(I-S(\underline{\phi}))C_k$$

and re-orthonormalized.

Referring back to FIG. **1**, ultrasonic beacon array **120** includes individual ultrasonic beacons **122** arranged in a regular pattern. For example, the beacons may be arranged on a square grid with a spacing of approximately 2 feet, preferably with an accuracy of 3 mm or less. A limited number of addresses are available for the beacons, in this embodiment only eight different addresses are available due to hardware limitations. Therefore, when the tracking device sends an IR command to an address, in general, multiple ultrasonic beacons will receive the signal and respond. Only the closest beacon with any particular address is used for range measurement. However, as multiple beacons may be responding to each IR command, the pulse detection circuit may be triggered prematurely, for example, by a pulse from a beacon triggered in a previous iteration, but that is sufficiently far away that its pulse does not arrive until after a subsequent iteration. In order to avoid this pre-triggering problem, pulse detector **522** (FIG. **5**) is only enabled during a time window about the expected time the desired pulse would arrive. This avoids false triggering by pulses from other beacons, or signals resulting from long time constant reverberation of previous pulses.

In the description the tracking and Kalman updating procedures, an initial location and orientation estimate is assumed to be known. This is not necessarily the case and an automatic acquisition algorithm is used by tracking device **100**. The limited number of addresses of ultrasonic beacons is used as the basis for an initial acquisition algorithm. Initially, the tracking device triggers beacons with each of the allowable addresses and measures the range to the closest beacon of each address. Then, the addresses of the four closest beacons are determined from the range measurements. The tracking unit includes a beacon map that includes the locations and addresses of all the beacons. The

beacons are arranged such that the addresses of the four closest beacons limit the possible locations to a small portion of the room. If there is ambiguity based on the closest beacons, the actual distances to the beacons are used in a triangulation procedure to resolve the ambiguity. The initial orientation is based on the relative range measurements to each of the microphones.

The overall tracking procedure can be summarized by the flowchart shown in FIG. **13**. First, the initial location and orientation is acquired (step **1310**) using the approach outlined above. The procedure then enters a loop that is executed once each time step. After waiting for the next time step (step **1320**), inertial measurements are received (step **1330**) and the tracked variables, $\underline{x}$, and the error covariance, P, are updated using the inertial measurements (step **1340**). If an ultrasonic range measurement that has not yet been processed is available (step **1350**), that range measurement is used to compute an error update, $\underline{\delta x}$, and updated error covariance, P(+), (step **1360**). The error update and new error covariance are then used to update the inertial tracker and the Kalman predictor (step **1370**). The procedure then involves determining whether further range measurements must be commanded at this time step (step **1380**). As three range measurements are made for each pulse but only one range measurement is used per time step, there may be a backlog of range measurements that will be applied in the upcoming time steps. Therefore, a new range measurement may not be necessarily for several future time steps. Taking into account the expected time of flight of the next ultrasonic pulse (which in general is more than a single time step), the procedure determines if an IR command should be sent to a beacon at this time step (step **1380**), the next beacon address is selected (step **1390**) and, if so, the IR command to that beacon is sent (step **1395**). The procedure then loops again starting at step **1320**, waiting for the start of the next time interval.

Several alternative approaches can also be used. In the described embodiment, only one range measurement is used per time step. Alternatively, all available range measurements can be used at each time step if the processor **130** has sufficient computation capacity. This alternative approach is implemented by looping from step **1370** back to step **1350** until all the range measurements are accounted for. Alternatively, rather than applying the Kalman updates for each of the scalar range measurements in turn, all can be applied in a single step using similar update equations for vector observations and correlated observation noise. Also, rather than deferring processing of a range measurement until the next time step, the range measurements can be incorporated as they arrive, and not synchronized with the inertial tracker updates.

The procedure described above can be combined with other measurement modes. For example, inclinometers can be used to provide measurements to the extended Kalman filter that allow correction of attitude drift. Also, rather than using three or more microphones which allow correction of all three degrees of rotation, two microphones can be used for range measurement in combination with a measurement mode such as inclinometers. In this way, some drift correction can be based on inclinometers, but a compass, which is sensitive to magnetic field variations, is not needed for drift correction. Many more than three microphones can also be used to provide greater redundancy and allow more rotation freedom.

As an alternative to mounting beacons in fixed locations in the environment, and microphones on the tracking device, which is often referred to as an “inside-out” arrangement,

this could be reversed in an "outside-in" arrangement. The tracking device then provides the ultrasonic pulses and a coordinated array of microphones senses the location of the tracking device. Note that by the time a pulse has reached a microphone, the tracking device will have, in general, moved on to a new location. This latency of measurements must be compensated for in a manner similar to the compensation of latency in use of range measurements described above.

Beacons **122** need not be mounted in a planar array. They could be mounted on walls as well as on the ceiling, or on other supports in the environment. For example, the beacons can be mounted on light fixtures. The number of beacons can be chosen to match the user's requirements, and the locations of the beacons can be chosen based on a variety of criterea, such as availability of suitable mounting points and geometric considerations, and the beacon map can be set to match the chosen number and locations of the beacons. The number of beacons in the constellation can be increased or reduced by the user, so long as the beacon map remains up to date.

The command signals from the tracking device to the beacons can be sent using other modes than IR transmission. For example, RF, visible, or acoustic signals can be used. The tracking device can also be wired to the beacons.

Two or more objects can be tracked in an "inside-outside-in" arrangement. Referring to FIG. **14***a*, tracking device **100** tracks its location as before. A second tracking device **1400** includes three addressable ultrasonic beacons **1410** arranged in a known relationship to one another. By triggering beacons **1410** to transmit acoustic pulses that are received at the URM **110** on tracking device **100**, tracking device can determine the relative location and orientation of the second tracking device. A further extension, which provides increased accuracy in the relative location and orientation estimates involves having a second inertial measurement unit fixed to tracking device **1400**, and transmitting its inertial measurements to tracking device **100**. If only a single beacon is placed on the second object, the relative location can be sensed using ultrasonic range measurements, without necessarily tracking the relative orientation of the second device.

Referring to FIG. **14***b*, a "mutual tracking network" made up of multiple tracking devices can be used. These tracking devices track their individual locations with respect to the locations of the other devices in the environment, including fixed beacons and other moving tracked objects. This can be done with an additional communication system coupling the tracking devices, such as an RF local area network.

In the above described embodiments, the "map" of the beacon array is assumed to be accurate. As the range measurements include redundant information, errors in placement of the beacons can be iteratively estimated and updated, thereby improving accuracy. Specifically, the placement errors of the beacons can be included in the state of the extended Kalman filter, and range measurements from each beacon would then contribute over time to estimating the placement errors. A separate initial automatic "mapping" mode can also be used in which, through range measurement from one or more locations in the room and triangulation calculations, the locations of the beacons can be determined. These automatically determined locations can be used as the known locations, or as initial estimates that are then further updated using the Kalman filter. In this type of approach, the beacons can be irregularly placed within the room without requiring that they be precisely positioned.

The tracking approach described above has several applications. A first application involves coupling the tracking device to a head mounted display. Referring to FIG. **15**, a head mounted display **1510**, allows a user to directly view a physical object **1520**, such as a work piece. Display **1510**, using the known location of work piece **1520** in the frame of reference of the room, superimposes information on the user's view of the work piece. For example, applying wiring harnesses to a large device, the superimposed information can include information related to the correct placement of the wiring harnesses. A similar head mounted display can also be used to provide the complete image viewed by a user in a virtual reality system, rather than superimposing an image on the real view seen by the user.

Another application involves tracking a camera location in a television application. Referring to FIG. **16**, a common technique in television production is to film a subject **1620** in front of a blank (typically monochrome) background and then to electronically superimpose another image (illustrated as **1630**) as a background. A difficulty with such a technique is that as camera **1610** moves, the background image should change to reflect the camera's motion. By attaching tracking device **100** to camera **1610**, the location and orientation of the camera is tracked and the background image can be automatically modified by an image processor that receives the changing position and orientation of the camera. This approach allows construction of large "virtual sets" which are stored in the image processor, and thereby multiple and changing camera "angles" can be used.

Another application involves sensing of motion of elements in an automobile, for example, in an automotive crash test. Referring to FIG. **17**, the motion of a dummy **1720** within a crashing automobile **1710** can be tracked using tracking device **100**. In addition, a second object, such as a point on the firewall can be tracked using an addition beacon **1730** using the inside-outside-in approach described above. This allows both tracking of the dummy in the reference frame of the automobile, and tracking of a point within the vehicle relative to the dummy.

Other applications include robotic navigation, tracking of inventory, assets, or personnel, shipboard virtual or augmented reality for damage control, film camera tracking, entertainment (e.g., theme parks and games), full body tracking for motion capture, and weapon tracking.

Alternative embodiments can also use other approaches to inertial tracking. For example, rather than performing attitude integration using a direction cosine matrix, attitude integration using Euler angles or quaternions can equivalently be used. Note that the linearized error propagation system matrix and driving noise covariance may depend somewhat on the particular tracking algorithm used. Also, the state of the Kalman filter can be changed, for instance, to include other terms. One example of this is to not only track accelerometer additive bias, as in the embodiments described above, but also to track multiplicative bias (e.g., error in scale factor) of the accelerometer signal, misalignment, and the speed of sound.

Other methods of range measurement can also be used, including acoustic phase, RF or optical time of flight, RF or optical phase, and mechanical cable extension.

Other methods of fusing inertial and acoustic measurements can be used instead of Kalman filtering. For example, neural network, rule-based reasoning, or fuzzy logic systems, or optimization methods, can be used to combine the measurements.

In the description above, only eight different ultrasonic beacon addresses are used. Alternatively, each beacon can be individually addressable, or a larger number of shared addresses can be used. If the beacons are individually

addressable, initial acquisition can be performed, for example, by having beacons also respond to "group" addresses, or to sequence commands addressed to individual beacons during the acquisition phase in such a way that tracking device can "zero in" to its initial location by first finding one beacon that is in range, and then searching for additional beacons that are closer and closer based on the beacon map known to the tracking device. Such an approach can also be used when the tracking area is made up of several different rooms. Initially, the room that the tracking device is in is and then the location within the room can be found.

It is to be understood that the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

1. A method for tracking a motion of a body comprising:

obtaining three types of measurements associated with the motion of the body, a first type comprising acoustic measurement, a second type comprising linear inertial measurement, and a third type comprising angular inertial measurement;

updating an estimate of a position of the body based on the second type of measurement;

updating the position estimate based on the first type of measurement; and

updating an estimate of an orientation of the body based on the third type of measurement.

2. The method of claim **1** in which the first type of measurement comprises acoustic ranging.

3. The method of claim **1** in which the estimate of orientation is undated based on the first type of measurement.

4. An apparatus for tracking motion of a body comprising:

three sensor systems configured respectively to obtain three types of measurements associated with motion of the body, a first type comprising acoustic measurement, a second type comprising linear inertial measurement and a third type comprising angular inertial measurement; and

a processor coupled to the three sensor systems and configured to update an estimate of a position of the body based on the second type of measurement, to update the position estimate based on the the first type of measurement, and to update an estimate of an orientation of the body based on the third type of measurement.

5. A tracking device comprising:

a sensor system including

an inertial sensor; and

a set of one or more acoustic sensors rigidly coupled to the inertial sensor; and

a processor programmed to perform the functions of

accepting inertial measurements from the inertial sensor;

updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements;

selecting one of a plurality of acoustic reference devices;

accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device;

updating the location estimate and the orientation estimate using the accepted range measurement.

6. The tracking device of claim **5** wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device.

7. The tracking device of claim **5**, wherein the set of one or more acoustic sensors includes two or more acoustic sensors.

8. The tracking device of claim **5**, wherein the processor is configured to

update a location estimate and an orientation estimate using the accepted inertial measurements by updating an uncertainty in the location and the orientation estimates; and

update the location estimate and the orientation estimate using the accepted range measurement by determining an uncertainty in the range measurement and updating the uncertainty in the location and the orientation estimates using the uncertainty in the range measurement.

9. A method for tracking the motion of a body including:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving a range measurement signal from the reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

10. The method of claim **9**, further comprising:

determining a range measurement based on a time of flight of the range measurement signal.

11. The method of claim **10** further comprising:

determining a range measurement based on a time of flight of the range measurement signal.

12. The method of claim **10** wherein transmitting the control signal includes transmitting a wireless control signal.

13. Software stored on a computer readable medium comprising instructions for causing a computer to perform the functions of:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

receiving a range measurement signal from the reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

14. A tracking system comprising:

an acoustic reference system including a plurality of acoustic reference devices; and

a tracking device including

a sensor system including an inertial sensor and a set of one or more acoustic sensors rigidly coupled to the inertial sensor, and

a processor programmed to perform the functions of accepting inertial measurements from the inertial sensor, updating a location estimate and an orientation estimate of the sensor system using the accepted inertial measurements, selecting one of a plurality of acoustic reference devices, accepting an acoustic

range measurement related to the distance between the sensor system and the selected acoustic reference device, and updating the location estimate and the orientation estimate using the accepted range measurement.

15. The system of claim **14** wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the acoustic reference device, and wherein each acoustic reference device includes a receiver for receiving the control signal from the sensor system, and an acoustic transducer for sending the acoustic signal.

16. The system of claim **14**, further comprising more than three acoustic receivers.

17. An apparatus for tracking motion of a body comprising:

two sensor systems configured respectively to obtain two types of measurements associated with motion of the body, one of the types comprising acoustic measurement, wherein the sensor system for obtaining acoustic measurement comprises greater than three acoustic receivers; and

a processor coupled to the two sensor systems and configured to update an estimate of either an orientation or a position of the body based on one of the two types of measurement, and to update the estimate based on the other of the two types of measurement.

18. The apparatus of claim **17**, wherein one of the types of measurement comprises acoustic ranging.

19. The apparatus of claim **17**, in which the other of the types of measurement comprises inertial measurement.

20. The apparatus of claim **17** in which the processor is configured to update an estimate of orientation based on the first type of measurement.

21. The apparatus of claim **20** in which the processor is configured to update an estimate of position based on the first type of measurement.

22. A method for tracking the motion of a body including:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

23. The method of claim **22**, further comprising:

receiving a range measurement signal from the selected reference device; and

determining a range measurement based on a time of flight of the range measurement signal.

24. The method of claim **22**, wherein transmitting the control signal includes transmitting a wireless control signal.

25. Software stored on a computer readable medium comprising instructions for causing a computer to perform the functions of:

selecting one of a plurality of reference devices;

transmitting a control signal to the selected reference device;

accepting a range measurement related to a distance to the selected reference device; and

updating a location estimate or an orientation estimate of the body using the accepted range measurement.

26. A tracking device comprising:

a sensor system including

an inertial sensor; and

a set of one or more acoustic sensors rigidly coupled to the inertial sensor; and

a processor programmed to perform the functions of accepting inertial measurements from the inertial sensor;

updating a location or orientation estimate of the sensor system using the accepted inertial measurements;

selecting one of a plurality of acoustic reference devices;

accepting an acoustic range measurement related to the distance between the sensor system and the selected acoustic reference device;

updating the estimate using the accepted range measurement.

27. The tracking device of claim **26**, wherein the sensor system includes a transmitter for transmitting a control signal encoding an identifier of the selected acoustic reference device, and each acoustic sensor includes a microphone for receiving an acoustic signal from the selected acoustic reference device.

28. The tracking device of claim **26**, wherein the set of one or more acoustic sensors includes two or more acoustic sensors.

29. The tracking device of claim **26**, wherein the set of one or more acoustic sensors includes more than three acoustic sensors.

30. The tracking device of claim **26**, wherein

the processor is configured to

update the estimate using the accepted inertial measurements by updating an uncertainty in the estimate; and

update the estimate using the accepted range measurement by determining an uncertainty in the range measurement and updating the uncertainty in the estimate using the uncertainty in the range measurement.

31. A tracking system for tracking the position of a body comprising:

a sensor system comprising a plurality of acoustic receivers rigidly coupled to a portable assembly; and

a plurality of acoustic reference devices arrayed at a distance from the portable assembly, wherein the acoustic receivers are arrayed on the portable assembly so that at least one of the acoustic receivers is positioned to receive signals from at least three of the acoustic reference devices regardless of the orientation of the portable assembly.

32. The tracking system of claim **31**, wherein the plurality of acoustic receivers comprises greater than 3 receivers.

33. The system of claim **32**, further comprising a processor programmed to select, based on the current orientation of the portable assembly, a subset of the acoustic receivers according to their ability to receive signals from the acoustic reference devices.

34. The tracking system of claim **31**, wherein for a majority of the orientations of the portable assembly, at least two of the acoustic receivers are positioned to receive signals from at least three of the acoustic reference devices.

35. A method for tracking motion of a rigid body comprising:

disposing a plurality of transducers in the environment;

mounting a plurality of transducers on the body;

measuring the range between a selected one of the transducers disposed in the environment and a selected one of the transducers mounted on the body;

predicting a range measurement between the selected transducer in the environment and the selected transducers mounted on the body;

updating an estimate of the orientation or position of the body based on the difference between the actual range measurement and the predicted range measurement.

36. The method of claim **35**, wherein the transducers disposed in the environment are acoustic emitters and the transducers mounted on the body are acoustic receivers.

37. The method of claim **35**, wherein the transducers disposed in the environment are acoustic receivers and the transducers mounted on the body are acoustic emitters.

38. The method of claim **35**, wherein the transducers disposed in the environment are optical emitters and the transducers mounted on the body are optical receivers.

39. The method of claim **35**, wherein the transducers disposed in the environment are optical receivers and the transducers mounted on the body are optical emitters.

40. The method of claim **35**, wherein the transducers disposed in the environment are radio frequency emitters and the transducers mounted on the body are radio frequency receivers.

41. The method of claim **35**, wherein the transducers disposed in the environment are radio frequency receivers and the transducers mounted on the body are radio frequency emitters.

42. The method of claim **35**, wherein at the transducers mounted on the body are disposed so that, in substantially all orientations of the rigid body, at least one of the transducers mounted on the body is positioned to be able to complete a range measurement with at least three of the transducers disposed in the environment.

43. The method of claim **42**, further comprising:

selecting one of the transducers mounted on the body and obtaining a range measurement between it and one of the transducers disposed in the environment.

44. A method for tracking a motion of a body comprising:

obtaining two types of measurements associated with the motion of the body, a first type comprising range measurement, and a second type comprising inertial measurement;

updating estimates of an orientation and a position of the body based on the second type of measurement; and

updating the estimate of the position of the body based on the first type of measurement, without first calculating a position estimate based only on the first type of measurement.

45. The method of claim **44**, in which the first type of measurement comprises acoustic ranging.

46. The method of claim **44**, further comprising updating the estimate of an orientation of the body based on the first type of measurement.

47. A method for tracking a motion of a body comprising:

obtaining two types of measurements associated with the motion of the body, a first type comprising range measurement, and a second type comprising angular inertial measurement;

updating an estimate of an orientation of the body based on the second type of measurement; and

updating the orientation estimate and an estimate of the position of the body based on the first type of measurement.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,176,837 B1 Page 1 of 1
DATED : January 23, 2001
INVENTOR(S) : Eric Foxlin

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 16,
Line 38, delete "determining a range measurement based on a time of flight of the range measurement signal" and insert -- obtaining an inertial measurement; and updating the location estimate or orientation estimate based on the inertial measurement --.
Line 40, "10" should be -- 9 --.

Signed and Sealed this

Eighteenth Day of June, 2002

Attest:

JAMES E. ROGAN

Attesting Officer *Director of the United States Patent and Trademark Office*